2017

A Graphical Approach to Analysis of Individual GSI Project Stormwater Mitigation in Urban Settings

Igor Bronz
University of Pennsylvania

A Graphical Approach to Analysis of Individual GSI Project Stormwater Mitigation in Urban Settings

Abstract

Within the field of Green Stormwater Infrastructure (GSI), a generalized, data-driven, quantitative approach into analyzing the stormwater mitigation efficiency of individual GSI projects with regard to their cost has not yet been published. Previous attempts have been made to determine the costs and benefits of using green infrastructure in certain municipalities, but these analyses quantify multiple aspects of green infrastructure, not just stormwater mitigation, and their conclusions are often specific to that municipality. To produce this missing component, a data table was created to break down the technical characteristics of interest for GSI projects and a graphing approach was used to compare the GSI projects to each other with the hopes of being able to make conclusions regarding the efficiency of certain projects at mitigating stormwater. Two types of linear-linear scale graphs were constructed: *stormwater mitigation capacity vs. cost*, and *stormwater mitigation capacity vs. area of BMP*. The goal of the *stormwater mitigation capacity vs. cost* graph is to determine which GSI projects are better at mitigating stormwater for their cost. This would prove useful for developers who desire to meet certain stormwater goals and want to have an understanding of how GSI project cost can vary, and why. The goal of the *stormwater mitigation capacity vs. area of BMP* graph is to determine whether GSI projects with deeper substrates or better technology are more efficient at mitigating stormwater despite having a smaller footprint, irrespective of cost. This would be useful for understanding how the stormwater mitigation efficacy of smaller, but higher quality projects varies compared to projects with a larger footprint, and would be of particular interest to those who desire to meet certain stormwater goals but have space constraints. Both graph types demonstrate clear variation between different GSI projects and their efficiency. Their relationships to each other coincide well with the respective GSI projects' intent and physical characteristics.

Disciplines

Earth Sciences | Physical Sciences and Mathematics

A GRAPHICAL APPROACH TO ANALYSIS OF INDIVIDUAL GSI PROJECT STORMWATER MITIGATION IN URBAN SETTINGS

Igor Bronz

MS Applied Geosciences
Hydrogeology

Fall 2017

Reader 1: Howard Neukrug, P.E., BCEE, D.WRE
Reader 2: James Anthony Sauder, P.E., P.G.

Table of Contents

Figures

ABSTRACT

A GRAPHICAL APPROACH TO ANALYSIS OF INDIVIDUAL GSI PROJECT STORMWATER MITIGATION IN URBAN SETTINGS

IGOR BRONZ

HOWARD NEUKRUG, P.E, BCEE, D.WRE

Within the field of Green Stormwater Infrastructure (GSI), a generalized, data-driven, quantitative approach into analyzing the stormwater mitigation efficiency of individual GSI projects with regard to their cost has not yet been published. Previous attempts have been made to determine the costs and benefits of using green infrastructure in certain municipalities, but these analyses quantify multiple aspects of green infrastructure, not just stormwater mitigation, and their conclusions are often specific to that municipality. To produce this missing component, a data table was created to break down the technical characteristics of interest for GSI projects and a graphing approach was used to compare the GSI projects to each other with the hopes of being able to make conclusions regarding the efficiency of certain projects at mitigating stormwater. Two types of linear-linear scale graphs were constructed: *stormwater mitigation capacity vs. cost*, and *stormwater mitigation capacity vs. area of BMP*. The goal of the *stormwater mitigation capacity vs. cost* graph is to determine which GSI projects are better at mitigating stormwater for their cost. This would prove useful for developers who desire to meet certain stormwater goals and want to have an understanding of how GSI project cost can vary, and why. The goal of the *stormwater mitigation capacity vs. area of BMP* graph is to determine whether GSI projects with deeper substrates or better technology are more efficient at mitigating stormwater despite having a smaller footprint, irrespective of cost. This would be useful for understanding how the stormwater mitigation efficacy of smaller, but higher quality projects varies compared to projects with a larger footprint, and would be of particular interest to those who desire to meet certain stormwater goals but have space constraints. Both graph types demonstrate clear variation between different GSI projects and their efficiency. Their relationships to each other coincide well with the respective GSI projects' intent and physical characteristics.

1.0 | Introduction

Green Stormwater Infrastructure (GSI) presents an integrated, cost-effective and aesthetically-pleasing way to control stormwater in comparison to more expensive and structurally invasive public works projects[1]. GSI can be defined as a range of soil-water-plant systems that intercept stormwater, infiltrate a portion of it into the ground, evaporate a portion of it into the air, and in some cases release a portion of it slowly back into the sewer system[2], while also providing important secondary benefits unrelated to stormwater management such as urban heat island effect reduction, increasing air quality and creating a habitat for plants and animals[1].

The combined value of all the benefits provided by GSI makes it an attractive option for future urban planning. As the extent of stormwater-related issues such as combined sewage overflow (CSO) became known, the City of Philadelphia has implemented a comprehensive GSI investment initiative called *Green City, Clean Waters* which is expected to save billions of dollars over traditional methods of stormwater management (grey infrastructure) such as building additional tunnels and canals to detain stormwater[3].

After the implementation of the *Green City, Clean Waters* initiative in 2011, Philadelphia has seen over 1600 separate green infrastructure sites at 440 locations across the city[4] and there is promise of many more to follow.

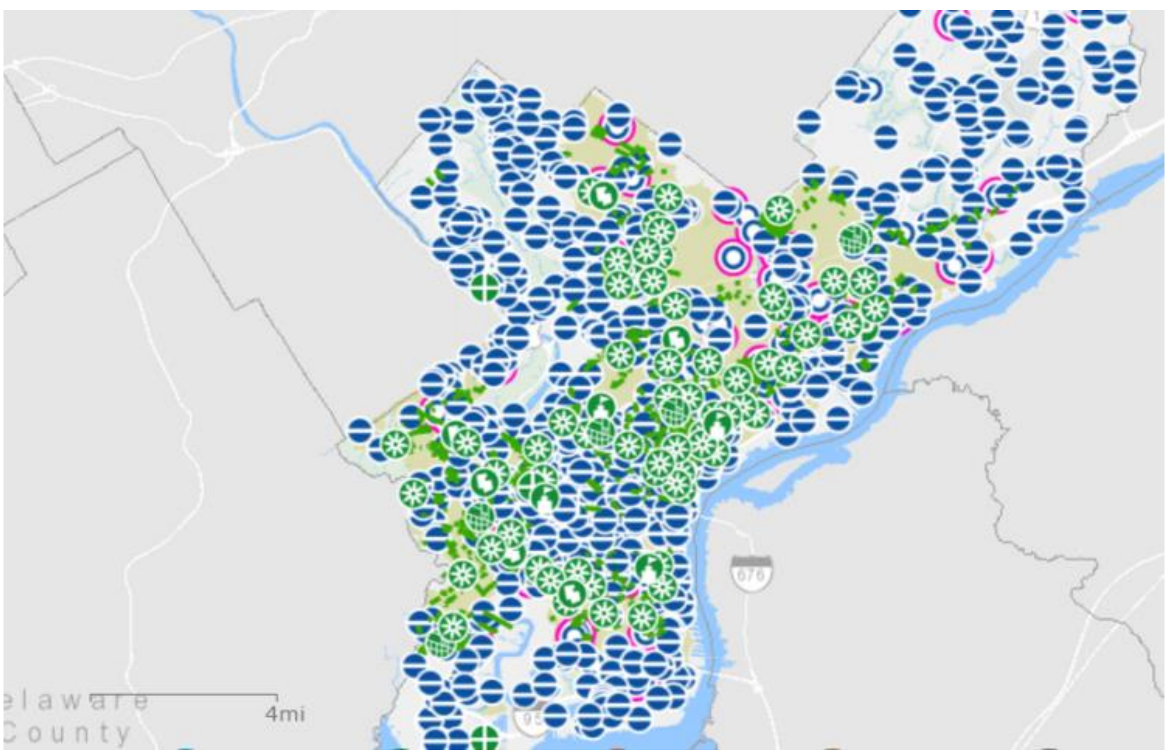


Figure 1: The public and private green infrastructure projects over the last 5 years in Philadelphia as a result of the Green City, Clean Waters stormwater management initiative. Blue circles indicate private projects while green circles indicate Philadelphia Water Department projects. Shoemaker Green is one of the blue circles. Source: [5]

Although Green infrastructure is becoming ubiquitous in many urban environments in the United States[6], it can be highly variable in cost. In Philadelphia, the stunning 1.25 acre Cira Green rooftop on 30th street and Chestnut, which provides a stormwater management system for the surrounding developments and a multi-use green space for visitors, costs approximately $2.6 million[7]. The University of Pennsylvania's own Shoemaker Green comes in at a cost of $8.5 million[8][9]. The Leed Elementary School at 4700 Locust street was able to retrofit a 6,500 square foot playground with porous pavement and greenery, but it cost them $500,000[4]. Even something as relatively simple and small scale as the 1,050 square foot Logan Gardens green roof in New York City costs $75,500[10][11].

Many of these high costs are associated with aesthetic and design features included in the GSI projects that do not provide additional stormwater benefits, or the addition of stormwater capacity beyond what is necessary. GSI projects such as Franklin Square School, Drexel Park and KidZooU on the other hand, can provide significant stormwater benefits for a comparatively lower cost[7].

As a brand new field, green infrastructure is in a phase of technical development, innovation and experimentation, and has only in the last few decades become a viable option for developers. It is reasonable to expect that GSI project costs are not well-aligned with their efficiency and that there would be a lot of room for improvement through additional innovation[12].

Unfortunately, there appears to be a profound lack of stormwater mitigation monitoring efforts and surprisingly little quantitative data available regarding the specifications of new GSI projects given the large scale of investments being made into GSI development. This is not to say that quantification does not exist; some municipalities monitor individual projects to better understand their efficacy as evidenced by the comprehensive findings of the NYC 2012 GI Pilot Monitoring Report[13]; however such monitoring efforts are made for only a relatively small fraction of total GSI projects implemented. The lack of monitoring has serious consequences for the field, as large-scale, data driven quantification of GSI project efficacy is an important step in further innovation.

The lack of monitoring efforts suggests that monitoring of GSI projects is a low priority for many developers. Indeed, these developers are often content with having resolved a specific localized runoff issue, obtained a LEED certification and/or having successfully marketed a new, 'environmentally-focused' recreation area as part of a larger development, even if the cost of the GSI project is significantly higher than was necessary or if the real efficacy of the given project remains unclear. To not bother with monitoring efforts may seem like a financially sound decision on an individual project basis between developers and owners, but the lack of data made available that results from such practices limits how much quantitative analysis could be performed and may hinder the field as a whole with regard to innovation.

While quantification of the value of GSI projects has been performed in the past, it has never been done on an individual project basis [1] [6] [9] [14] [15] [16]. The most effective first step in quantifiably demonstrating the advantages and disadvantages of individual GSI projects is to use a graphical approach that would compare these GSI projects along a set of key characteristics, such as cost, project area and capacity of stormwater mitigation, to better understand what makes certain GSI projects more efficient at mitigating stormwater than others. This understanding would allow public and private entities to know the correct type of GSI project to implement in specific situations which would allow a more efficient allocation of resources with regard to reducing stormwater runoff on a municipality-wide scale by eliminating costly expenditures and correctly identifying GSI projects with under-utilized capacity.

2.0 | Literature Review

As cities throughout the world continue to grow in population and expand, water takes on an increasingly crucial role. It is predicated that by 2050, urban and industrial water usage will double [17]. The waterways which surround these urban centers will take on an even greater level of importance with regard to commerce and recreation, but will also become more vulnerable due to increasing population size. One effective way to mitigate the issues that arise from expanding urban centers is through green infrastructure. Green Stormwater Infrastructure (GSI) can be defined as a range of soil-water-plant systems that intercept stormwater, infiltrate a portion of it into the ground, evaporate a portion of it into the air, and in some cases release a portion of it slowly back into the sewer system[2].

One of the primary objectives of GSI is to overcome challenges related to Combined Sewage Overflow (CSO). Some large cities in the US, such as New York City and Philadelphia use a combined sewage system that takes in both sanitary sewage and stormwater runoff. The use of a combined sewage system dates back to the 19th century, implemented to relieve rapidly developing urban centers of unsanitary conditions that contributed to the spread of illnesses such as typhus and cholera[18]. In modern times, the combined sewage is treated at a wastewater treatment plant instead of being emptied into the nearest body of water[18]. However, during intense storm events, the wastewater treatment plant may not be able to take in the large volume of combined sewage which causes some portion of the untreated sewage to be discharged into a body of water or unto bare soil. These are known as CSO (combined sewage overflow) events and produce roughly 16 billion gallons of untreated discharge from 164 point sources annually[19].

CSO is a result of stormwater runoff into sewer systems which increases proportionally with impervious surface area (concrete, asphalt), and threatens to pollute and erode waterways that are crucial to the health of urban centers[20]. GSI prevents urban drainage systems from overflowing and polluting waterways with untreated sewage by providing a system in which stormwater can infiltrate through a permeable surface and remain within the GSI system for some amount of time before entering the sewer or be detained within the GSI system entirely, which allows the wastewater facility time to process the sewage. This staggered runoff effect allows the drainage system to cope with large quantities of water without overflowing [12].

The use of GSI for stormwater management has numerous environmental, economic and social benefits. A study that examined 479 GI (Green Infrastructure of all types including projects not specifically constructed for stormwater mitigation purposes) sites across the United States found that 44% of GI projects reduced costs for their communities, compared to 31% of projects that increased costs[21]. A comprehensive GSI plan in Philadelphia titled *Green City, Clean Waters*, is expected to cost $4.8 billion less than a comparable "grey infrastructure" (use of water tunnels and canals) plan to accomplish the same stormwater goals, without factoring in other benefits[1]. The green infrastructure plan in New York City is expected to cost $1.5 billion less than its grey infrastructure counterpart[3]. These cost savings are only related to stormwater and do not take into account the myriad other benefits of GSI which greatly increase its value over a 40-year period[1].

Despite the savings compared to grey infrastructure, GSI costs can still be quite high. For example, Shoemaker Green, a 2.75 acre green space located at the University of Pennsylvania came in at a cost of $8.5 million[8][9]. Cira Green, a green roof, reported a cost of $2.6 million[7]. This raises the question of whether the efficacy of these individual projects warrants their cost. A number of cost-benefit analyses were performed on green infrastructure projects[3] including an analysis of the cost-benefit of GI in Lancaster, PA[14], a compilation of case-studies that examine possible elements that factor into a cost-benefit analysis for GI[9] and an assessment of the green vs. grey options that are proposed for Philadelphia in dealing with CSO issues[15].

The previously cited cost-benefit analyses are either spatially specific (occurring only within the confines of one specific area) or broad in scope (examining all aspects of a GSI within a given municipality or county). Other cost-benefit analyses provided by the EPA exhibit similar qualities of spatial specificity, overly large breadth of scope or lack of sufficient quantifiable data on an individual project basis. Researchers have conducted surveys of GSI municipality-wide plans and outlook across numerous cities[6] and others have examined GSI using an integrated approach combining hydrologic, economic and legal concepts[16].

An approach that takes a cross section of specific GSI projects across several American cities and analyzes their stormwater mitigation efficacy relative to their cost remains uncharted territory. To accomplish this goal, a data table would need to be populated with relevant information concerning specific GSI projects. The information that this data table would use would include data that could be classified under the three following characteristics:

Internal characteristics of the GSI project, such as area managed, depth of stormwater mitigated, cost and number of trees planted

External characteristics of the GSI project which relate to its setting such as the average precipitation of the city where the project is located and the inflation rate of the country or municipality (if they differ).

Derived characteristics of a GSI project which must be obtained by performing calculations on the internal and external characteristics. An example of a derived characteristic is stormwater mitigation capacity (gal/yr).

Of the three types of characteristics mentioned above, the most reliably obtainable are the external characteristics. Daily precipitation records for the years 2000-2016 could be readily obtained from the NOAA National Center for Environmental Information[22] and because all GSI projects are from within the United States of America, an average inflation rate of 2.4% (from 2000-2016) was used[23].

The level of detail of the data provided by a publication can vary significantly from one publication to another. Generally, the highest quality internal data could be found in monitoring publications such as the *NYC 2012 GI Pilot Monitoring Report*, which provides data such as depth of the project, type/composition, area of the project (it's 'footprint') and area managed by the project[13]. Despite that, cost data was omitted from this publication which must be obtained separately; however the quality of the experimental data is still very high which provides a reliable resource to gather internal characteristics. Publications such as *Exceeding Intent: A Precedent library of Exemplary Green Stormwater Infrastructure Projects*, while not explicitly scientific in presentation or approach, contain valuable technical data about specific GSI projects[7]. Other types of publications only provide small pieces of useful data that could describe the characteristics of a GSI project but are considered lower quality as a consequence[24]. These publications require derivation of GSI characteristics where possible to allow projects presented in these publications to be considered useful.

At the other end of the spectrum in terms of thorough information that can describe internal characteristics are consumer-facing landscape architecture websites[25]. Landscape architecture firms rarely divulge any technical data about their work to the public, and require the researcher to reach out over email or by phone for a chance at obtaining data. As a result, their data is considered too sparse to be useful for these purposes; however this is not the case for all landscape architecture sites.

Derived characteristics are characteristics about a GSI project that must be obtained by mathematically manipulating internal and external characteristics already known about that GSI project. Methodologies to derive important information about a GSI project are available both from GSI-focused[26] and non-GSI focused publications. GSI-focused publications such as *CNT: Value of Green Infrastructure*[26] explicitly provides calculations for GSI projects, while non-GSI publications [27] [28] could provide useful information for deriving the characteristics of a GSI project without the publication ever exploring green infrastructure specifically. One example of a non-GSI focused publication providing useful data is a study that examined the average volume of rainwater intercepted by 19 species of trees[27] and a study that analyzed the relationship between runoff and slope of a surface[28]. Certain publications can provide information about a GSI project that they have derived themselves[7] in which case the methodology must be transparent, and some publications may omit internal data that is normally presented as part of a monitoring study, and this data must be derived from the data that is available, if at all possible.

3.0 | Methodology

The key first step in graphically analyzing the stormwater mitigation characteristics of individual GSI projects is to create a data table using Microsoft Excel that can describe a GSI project using relevant criteria. The data table consists of 41 GSI projects in total. Of those 41 projects, 3 GSI projects were omitted from all graphical analysis (reasoning explained in **Section 3.2**), and another 8 were omitted from any analysis that factors in cost due to missing cost data.

3.1 | Data Table Criteria and Key Assumptions

The term BMP (Best Management Practice) is used in the following column headings. BMP(s), in this case, is shorthand for discussing one or multiple GSI projects.

Name: The name used to call each GSI project was preferably chosen as the name given to it by the developer, however if the name given to the project by the developer was not apparent, a more descriptive name was assigned to it. The assigned name used a combination of location and project type, for example: Franklin Square Curb Ext. was the name given to a curb extension that was built near Franklin Square in Baltimore. This name is meant to be unambiguous, meaning that if there are several curb extensions near Franklin Square, they would all be considered one GSI project.

Location: The location for a GSI project is determined by the municipality where it is located. The GSI project must be located within the city limits of a municipality to be considered a part of that city. For example, if Yale University constructed a green roof, it would be considered a part of New Haven, Connecticut even though New Haven is considered a part of the New York Metropolitan Area.

Average Precipitation (in/yr): To determine the average annual precipitation for a GSI project, daily precipitation data was retrieved from the NOAA National Center for Environmental Information[22] for the years 2000-2016. The total rainfall of >0.05 in/day for years 2000-2016 was summed and divided by 17 (number of years) to obtain the annual precipitation data. The number obtained sometimes differed significantly from the annual precipitation that was obtained from U.S Climate Data[22]. For example, the average precipitation from 2000-2016 for New York City (measured at John F. Kennedy Airport) was 43.17 inches[22], while the annual precipitation measured for Central Park between 1961-1990 was 46.23 inches[29]. The difference in annual precipitation between the two numbers seems significant (>2 inches +/-); however the 2000-2016 data seemed more relevant for the purposes of studying GSI because it is more recent.

The purpose of using only rainfall events above 0.05 in/day is that for any events below 0.05 in/day, the precipitation would be lost to evapotranspiration immediately therefore using the total annual precipitation without making this correction would cause GSI projects to report stormwater mitigation capacities higher than what is actually happening. Although both sources are considered reliable, precipitation trends may differ over the course of 30 years and it is more likely that the 2000-2016 interval would more accurately predict current and future precipitation trends than the 1961-1990 interval. The spatial difference between the rain gauges (Central Park vs. JFK Airport) is not believed to create a difference in the precipitation recorded as the distance between the two areas is not very large. In addition, the 2000-2016 interval was used to determine the amount of rainfall mitigated by a GSI project of known depth, therefore it would be more prudent to use annual precipitation for the same interval.

This does not mean that the 2000-2016 interval is entirely predictive of future precipitation trends which can change drastically, especially many decades later, only that it is more reliable than an older trend. Several GSI data points were located in smaller nearby towns from the larger municipalities and the 2000-2016 precipitation trend was not available from the NOAA National Center for Environmental Information, therefore a local rain gauge was used that uses an older precipitation interval. The annual precipitation in these cases does not differ significantly from the 2000-2016 interval for the larger municipality (<2 inches +/-), and is not expected to cause a discrepancy in the data.

Mitigation %: The Mitigation Percentage is an estimate of the average percentage of rainfall that a GSI project prevents from entering the sewer during storm events over the course of a year. This number is obtained either directly from monitoring data, or derived from the advertised depth of a GSI project and is a necessary component in calculating the stormwater mitigation capacity of a GSI project. If the mitigation percentage cannot be obtained from the monitoring data, it is derived from depth by using the NOAA National Center for Environmental Information[22] 2000-2016 interval for daily precipitation. If a GSI project is known to have a depth of 1-inch, all rainfall events that produce between 1 inch and 0.05 inches of precipitation will be entirely mitigated (meaning no stormwater enters the sewage system) and any storm that produces more than one inch of precipitation will be mitigated by one inch. For example, if a 3-inch design storm occurs over Philadelphia, a 1-inch GSI project will insure that two inches of stormwater will enter the sewage system that would have fallen on the area managed by that project.

This derivation was performed for each large city where daily precipitation data for the 2000-2016 interval is available. The steps taken to calculate the mitigation % of a GSI project with a depth of 1-inch are as follows: The daily precipitation was ordered from greatest to least to allow calculations to be performed for different intervals of daily precipitation. The volume of rainfall >0.05 inches was summed. Then, one inch was subtracted from all precipitation values >1 inch in a separate column. This is necessary to illustrate that the GSI project mitigates all storms by one inch. The following general formula could now be used to calculate the volume of rainfall mitigated by a GSI project with a mitigation depth of X inches:

$$1 - \frac{\sum(Precipitation\ events > X\ inches) - X\ inches}{\sum Precipitation\ events(> 0.05\ inches)}$$

This method can be applied to any depth of mitigation that is desired, such as X = 1.5 inches or X = 2 inches.

The mitigation percentage, whether derived or observed through monitoring, does not guarantee that exactly this much rainfall will be mitigated in a given storm. For example, if a 15-minute design storm (A critical rainfall event that is used for assessing the flood hydrograph of a certain return period[30]) produces 1 inch of rainfall over 15 minutes at a high intensity of 4 in/hr, a large portion of the rain that falls on the GSI project will run off into the sewage system because the infiltration rate of the substrate used by the GSI project will be smaller than the rate at which water is hitting it, producing overland flow. Essentially, the GSI project will not be able to 'absorb' the water fast enough.

On the other hand, it may be possible for a 1-inch GSI project to mitigate more than 1-inch of rainfall if a design storm produces 2 inches of precipitation over the course of 24 hours through relatively mild but constant precipitation because the stormwater will drain out of the GSI project throughout the day either through evapotranspiration or release into the sewage system thus freeing up extra capacity[31]. These are two extreme cases where the mitigation % figure may prove misleading. It is also important to note that because the mitigation % is calculated based on the 2000-2016 precipitation interval, it is accurate to only the precipitation volume and frequency that matches this interval. If precipitation rates become significantly smaller or larger than what the 2000-2016 interval shows, the 1-inch and 1.5 inch mitigation % values would need to be re-calculated.

All GSI projects used in the analysis were controlled for slope. Highly sloped surfaces (15%+) can significantly increase the quantity of runoff on that surface independent of the substrate or surface roughness characteristics. Average slopes of greater than 7% were not used, so including slope in the runoff calculation was not necessary as slopes under 7% do not show significant increases in surface runoff[28].

Specific Depth Mitigated (in): The depth of a GSI project is the number of inches of rainfall that it can mitigate over its given area. This value is closely tied to mitigation percentage in effect; however it is advertised by the developer much more often than mitigation percentage likely as a result of stormwater control initiatives such as *Green Cities, Clean Waters* in Philadelphia requiring that at least the first inch of rainfall be mitigated[2]. The mitigation percentage can be derived once the depth and location of the GSI project are known by performing the calculation described in the previous section. If the depth of a project is not known and the project had been built after the creation of a credit-providing stormwater initiative such as *Green Cities, Clean Waters*, the minimum allowable depth specified by the initiative is used, which in this case, is 1-inch. If the depth mitigated of a GSI project is unknown and it was constructed prior to the start of a stormwater credit initiative and no further monitoring has been performed, this project was excluded from the data table.

One interesting type of GSI project where the depth mitigated is rarely provided is parks. A study in Cuyohoga Falls, Ohio found that a 24,000 square foot park drains a 3-acre residential area by 1 inch[31]. A calculation was performed to convert the finding of this study into a usable depth mitigated:

$$\left(\left(\frac{3\ acres * 43{,}560\,\frac{ft}{acre}}{24{,}000\ ft}\right) * .4 + 1\right)$$

A value of .4 was used as the runoff coefficient for a residential area[32], and the +1 is added to account for the size of the park itself. The equation provides a mitigation depth of 3.17 inches for parks. A complex retrofit GSI project called Shoemaker Green in Philadelphia, which is expected to exhibit the same capacity for stormwater mitigation as a park, was observed to have mitigated nearly all of the stormwater from a 3.16 inch storm[7], which is strikingly close to the mitigation depth calculated above, validating this method. The park in Cuyahoga Falls, Ohio[31] was operating at maximum capacity, however the topography surrounding other parks could drastically change how much water comes into the park during a storm event so there may be a degree of error present in assuming the mitigation depth of every park to be 3.17 inches.

Additionally, using the SCS Curve Number method with a curve number of 45 for parks that are in good condition with roughly 75% grass cover, a relatively permeable soil type and an $I_a = 0.2S$ demonstrates that these parks will not produce any runoff for rainfall events under 3.2 inches, which is consistent with the previous calculation and the Cuyohoga falls study [31] [48].

Area of BMP (sq. ft.): This is the footprint area of the GSI project itself. All projects analyzed in this report were essentially 'flat' - none of the projects analyzed were multi-level projects whereby the area of the project would be significantly greater than its footprint. For GSI projects such as those, the Area of the BMP would have to take into account the area of each level.

Area Managed (sq. ft.): The Area Managed is the area that a GSI project is designed for to control stormwater runoff. For example, a relatively small bioretention pond could be constructed near a parking lot to be able to drain the stormwater from the entire lot. The Canarsie Parking Lot is one such example of a 1,600 ft. bioretention pond that fully retains the stormwater that runs off a 36,000 sq. ft. parking lot. For the purposes of stormwater mitigation capacity, this value is more useful than using simply the area of the BMP because it better describes the GSI project's design and purpose.

For situations where the Area Managed is not provided, Google Earth Pro could be used to estimate the area managed by a GSI project based on other descriptive criteria. Shoemaker Green in Philadelphia is described as managing the stormwater from the surrounding buildings on its lot [7] [9], but no hard estimate is provided on the total area managed. In this situation, Google Earth Pro could be used to create a polygon whose area could be measured around a building such as the Free Library of Philadelphia as seen in **Figure 2.**

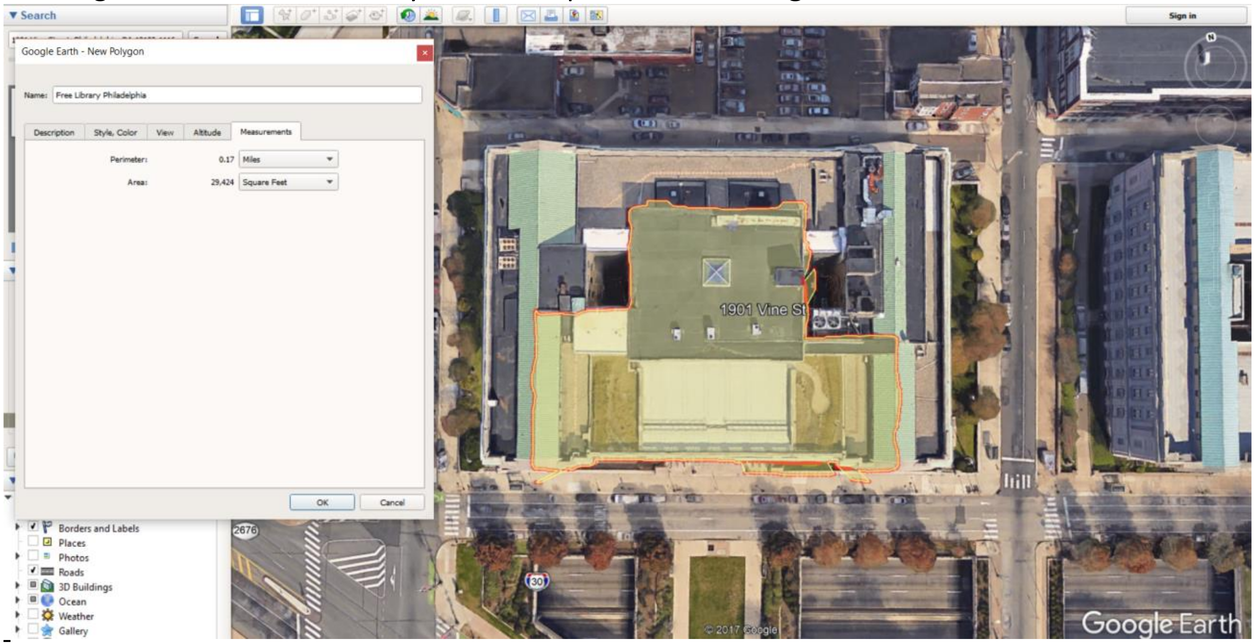


Figure 2: Google Earth Pro image of The Free Library At Philadelphia located at 1901 Vine St with a polygon (at 40% opacity) drawn around the likely area that the two green roofs (two green rectangles on roof) will capture stormwater from. Rough edges indicate a polygon rendering error from Google Earth Pro and do not affect the area managed displayed, as the true edges of the polygon only contain the roof of the building.

In cases where the description is not provided or proves insufficient to accurately determine the area managed of the project, Google Earth Pro provides elevation data which would allow for an estimate of the area managed under the following assumptions: that all points of elevation are on the same level or higher than the GSI project in question, that stormwater will never flow over a point of higher elevation to reach a point of lower elevation, that there are no separate or unconnected GSI that would capture the stormwater within the polygon used for the GSI project in question and that there are no storm drains or other separations within the polygon of the GSI project's area managed. For example, if you have a green roof that takes up 40% of a rooftop while the other 60% is a conventional roof, it would be assumed that the green roof manages the stormwater for the entire roof providing that no portion of that roof violates the previous assumptions. Similarly, if the terrace of a large building has a green roof, but the roof of the same building is a conventional roof that is several stories higher than the terrace, it would be assumed that this terrace would control the stormwater than runs off the roof of the building.

This approach is used because in the absence of data, it is logical to make the assumption that the developers of a GSI project designed the project to reduce the maximum volume of stormwater possible, and therefore would want to funnel all runoff from points of higher elevation on the building into the GSI project. This assumption is not made for points of lower elevation than the GSI project because that would require a pumping system, which are uncommon.

A level of discretion with regard to hydrologic principles is needed for this approach. The Free Library of Philadelphia in **Figure 2** is one such example, where the complicated rooftop is separated into several segments that appear to have different elevations and slopes. Creating a polygon around the entire roof of the building would greatly overestimate the area managed because it cannot be assumed unless otherwise specified via a drainage system that the stormwater runoff on the north side of the rooftop will reach the green roofs on the south side of the rooftop. Similarly, because a part of the slope of the eastern and western portion of the rooftop in **Figure 2** faces away from the green roofs, it cannot be assumed that stormwater will drain into the green roof. For the previous reason, the polygon only considers the water that can reasonably flow into the green roof area with consideration of hydrologic principles.

 # Tree Eq. Val.: This is the number of tree equivalent values, which is used to describe the number of trees on the GSI project. Trees can play an important role in mitigating stormwater by intercepting an average 25% of the water that falls on them during a given rainstorm[27]. Since not all trees are the same size, larger trees would intercept a greater volume of stormwater than smaller trees, creating a need for an equivalence value. A tree canopy is estimated to be roughly circular from an aerial perspective, so the area of a circular tree canopy that is 20 feet in diameter would be four times larger than the area of a tree canopy that is 10 feet in diameter and so on. For this reason, a tree canopy that is 10 feet in diameter is considered a standard tree, while trees canopies that are closer to 20 feet would count as 4 standard tree equivalents therefore a 40 foot diameter tree canopy would count as 16 tree equivalents. Many GSI projects plant shrubs or saplings which can also play a significant role in intercepting stormwater. In the case of densely packed shrubs, each shrub was assumed to be 2 feet in diameter therefore 25 shrubs or saplings would need to be counted to produce one tree equivalent value. Trees were counted using Google Earth Pro and their sizes were documented using the measure tool. For GSI projects that contain a very large amount of trees or shrubs, estimates counts by the developer were often provided. The diameter of trees was rounded to the nearest 5 feet for ease of calculation, so if a tree were 18 feet in diameter, it would be counted as a 20 foot tree.

Tree Intercept (gal/yr): This is the total number of gallons of stormwater that the trees will intercept annually. The Tree Intercept (gal/yr) value could be defined using the following formula:

$$[\#\, Tree\ Eq.Val.] \ * \pi(5\ ft)^2) * \left(0.25 * \left[annual\ precipitation\ \left(\frac{in}{yr}\right)\right]\right) * 144\frac{in^2}{ft^2} * 0.00433\ gal/in^3$$

In GSI projects that contain a large number of trees, the volume of water intercepted by the trees is not insignificant, sometimes adding an extra 1.5% to total capacity (calculated from the data table in **Figure 5**). As stormwater mitigation is not the primary purpose of trees and shrubs, the fact that they do provide increased stormwater mitigation capacity are notable. Trees and shrubs are primarily used for heat island effect reduction, air filtration, animal habitats, shade for recreation and aesthetic purposes[1].

Total Capacity (gal/yr): The total capacity is the volume of stormwater in gallons that a GSI project is estimated to remove from a Combined Sewage Overflow (CSO) event in a given year. Removal from a CSO event is defined as either entirely the stormwater from entering the sewer system, or staggering the rate at which the stormwater enters the sewer system such that it does not contribute to a CSO event. The Total Capacity (gal/yr) could be defined using the following formula:

$$\left[Avg. Precipitation \left(\frac{in}{yr}\right)\right] * [Mitigation\,\%] * [Area\ Managed\ (ft^2)] * 144\frac{in^2}{ft^2} * 0.004433\frac{gal}{in^3} + [Tree\ Intercept\left(\frac{gal}{yr}\right)]$$

A key assumption made in this report with regard to estimating the volume of stormwater that a GSI project prevents from entering the sewage system as part of a CSO event is that the number of gallons mitigated remains constant regardless of distance between the GSI project and the point source of CSO release. In reality, due to modern Real-Time Decision Support Systems (RT-DSS) and the gating technology that they employ to maximize water storage within the sewer, inflow that occurs into the sewage system further from the outlet will contribute less to a CSO event than inflow that happens into the sewage system closer to the outlet[33]. If the stormwater will remain in the sewage system for a longer period of time, there is a greater chance that its flow will be staggered by the RT-DSS causing sewage to flow more fully within the pipe than it normally would. As a result, less of the sewage further from the outlet will exit the system as a CSO. To actually model the behavior of the RT-DSS would require the use of software that is outside the scope of this report. Distance from GSI project to outlet and the decline in volume over distance were characteristics that were not able to be gathered for the GSI projects used. Creating a 'distance from outflow' modifier coefficient to apply to the Total Capacity (gal/yr) value would certainly be an interesting future endeavor.

Type: GSI projects were separated into different types of best management practices (BMPs) depending on their design. It is necessary to classify GSI projects by the type of BMP they use for comparison purposes as different types of BMPs come with different average costs and their own advantages/disadvantages. The type of the GSI project is determined by the type of technology the project uses to control stormwater. Some GSI projects use the stormwater control features of several different types of BMPs and as a result, are given two types that represent the dominant features, meaning that they can be compared to GSI projects of either type.

> Green Roof (extensive): Extensive green roofs tend to have a minimum substrate depth of 3-6 inches, a weight of 15-50 lbs/ft^3, lower cost than intensive green roofs, require less maintenance and can support a limited number of plant species such as mosses, sedums, succulents, herbs and grasses[34][35]. Both single-course and multi-course extensive green roofs were counted under Green Roof (extensive) as there is not a significant difference in substrate thickness, which is assumed to be the most important factor for stormwater mitigation capacity as a result of the substrate's storage capacity.

Green Roof (intensive): Intensive green roofs tend to have a substrate depth of 7-24+ inches, a weight of 35-80+ lbs/ft^3, with fully saturated weights of 80-120+ lbs/ft^3 ,higher cost than extensive, multi-course extensive, semi-intensive and intensive green roofs, require the highest level of maintenance and can support most plant types including trees and farming operations[34][35].

The type of green roof used is either provided by the developer or could be surmised based on the substrate depth and type of plants used. Semi-intensive green roofs tend to have depths of 5-7 inches[34]; however no data on this type of roofs was collected. **Figure 3** illustrates the types of green roofs that are used and the technology that goes into them.

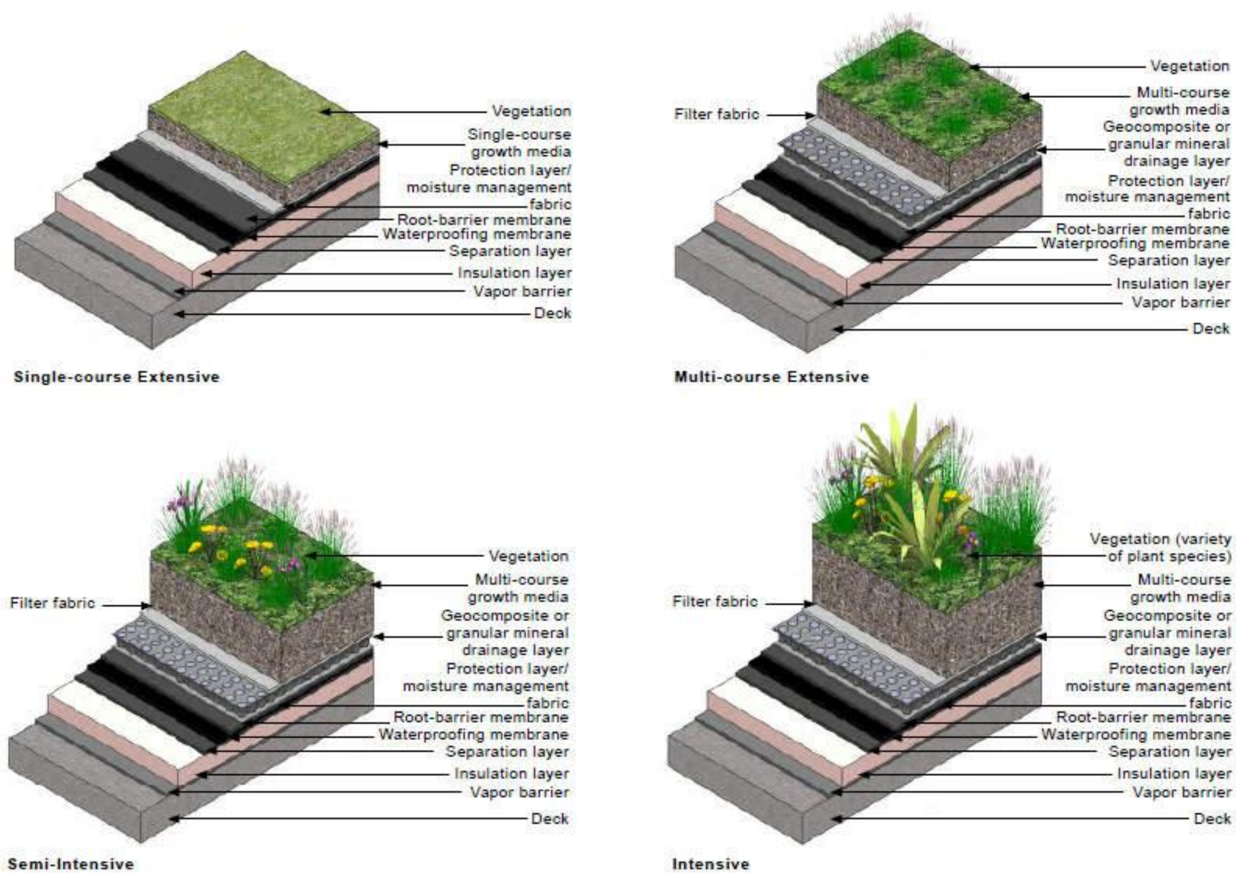


Figure 3: An illustration of the four green roof types and their components. Semi-intensive roofs were not used in the data collection. Source: (Sustainable Facilities Tool[36])

Bioretention: A bioretention BMP is a patch of land usually constructed as a depression that functions by slowing the flow rate of runoff, filtering stormwater of particulates and chemicals using sediment such as sand and silt, and detaining water during a storm event[37]. Bioretention basins (often referred to as bioswales or rain gardens) tend to use wetland grasses that thrive in standing water conditions. Bioretention BMPs are usually smaller in area than parks and are built with the intent of having a visible amount of standing water after a storm event.

Park: Parks in this case refers to urban parks, which are a type of BMP that often resemble natural woodlands or savannahs and are usually constructed for recreation purposes with stormwater management being a secondary goal[38]. Despite this, parks tend to be very effective in mitigating stormwater runoff due to their larger area, higher quantity of trees and deep layer of substrate[31]. Stormwater management, heat island effect reduction and the preservation of animal habitats take on a stronger degree of importance in the construction of modern urban parks than they have done in the past as municipalities have begun to recognize the many natural benefits that urban parks contribute to inhabitants of cities[38]. For these reasons, modern urban parks have begun to use porous concrete for their walkways and strategic design to maximize their effectiveness in accomplishing those tasks.

Porous Pavement: Porous pavement refers to types of concrete mixes that allow for water to quickly infiltrate through the concrete and into the soil beneath to minimize surface runoff. In settings where the construction of other types of BMPs would not be appropriate (such as parking lots), porous concrete can be used to reduce stormwater runoff.

Curb Bumpout: A stormwater curb bumpout is a vegetated curb extension that protrudes into the street either mid-block or at an intersection, creating a new curb some distance from the existing curb. A bumpout is composed of a layer of stone that is topped with soil and plants. An inlet or curb-cut directs runoff into the bumpout structure where it can be stored, infiltrated, and taken up by the plants via evapotranspiration[39]. An example of a curb bumpout can be found in **Figure 4.** In addition to being effective BMPs for the reduction of stormwater entering the sewer, curb bumpouts reduce the amount of impervious surface that would otherwise be present on the road.

Figure 4: A stormwater curb bumpout in Philadelphia, PA. Source: (Philadelphia Water Department[39])

Date Completed: This is the year during which a GSI project becomes fully completed. Certain GSI projects may take several years to construct.

Cost (dollars): The cost of the GSI project in dollars, as provided by the developer or a separate reputable source that would reasonably have intimate knowledge of the project's cost such as a regulatory agency, stormwater-credit providing body (such as the Philadelphia Water Department) or taken from a published work by a reputable third-party with which the GSI project is registered [7] [40]. The cost for some of GSI projects analyzed was held confidential. Special care was taken to find the cost of the implementation of the GSI project with only the labor, materials and design that went into its construction, and not the price of real estate in the area. As such, only GSI projects were used that were constructed on land that was already previously owned by the developer or built on publically-owned land through a public entity. The cost does not take into account the different costs of labor from one municipality to another or whether unionized labor was used in the construction process, which may create some level of error in the cost of a GSI project. Additionally, miscalculations, mechanical failures, planning failures, differences in charge rates between landscape architecture firms and cases of miscommunication between the various parties involved are just some of the variables involved which may increase the cost of a GSI project and would be very difficult to account for within the scope of this report.

Adjusted Cost (dollars): This is the adjusted cost in dollars of a GSI project for 2017 after taking into account the inflation rate. Because some GSI projects have been constructed several years prior to others and cost is one factor of comparison for between these individual projects, the inflation rate must be taken into account to insure that the cost of two separate projects is more readily comparable. This value was calculated using the following equation while using an average annual inflation rate of 2.4% for the 2000-2016 interval[23].

$$[Cost(dollars)] * (1 + 0.024)^{(2017-[Date\ Completed])}$$

The inflation rate used for the Adjusted Cost (dollars) calculation is subject to change in the future. Additionally, 2.4% is the average annual inflation rate for the United States of America; statewide and local inflation rates and future regulations could cause the cost to fluctuate or be misrepresented.

Annual Cost (dollars): The annual maintenance cost in dollars of a GSI project was estimated to be 2% of the initial cost [41] [42]. This value is considered a simplified estimate of the true maintenance cost of the GSI project, which could vary by type of BMPs used, is not necessarily constant from one year to another and could be seriously affected by externalities such as a particularly damaging flood, possible neglect by the owner or structural issues with the area where the GSI project is constructed. If the true maintenance costs of every GSI project analyzed was recorded over a period of 20 years, a significant amount of variability is expected due to the numerous factors that cannot be controlled within this scope.

Link: This is the most reputable or complete web URL link that could be obtained for a specific GSI project that describes its internal/derived characteristics. Although only one source is present is present on the data sheet, certain GSI projects were researched using numerous sources, with only the most complete source being displayed.

3.2 | Graphing Approach

Graphing was performed using Microsoft Excel 2010. Four graphs were constructed representing the three types of GSI projects analyzed and one combined graph with all GSI projects included. Each graph compared the stormwater mitigation capacity of a GSI project in gallons/year on the x-axis and cost in thousands of dollars on the y-axis. GSI projects that were classified as more than one type would appear on the respective graphs for their types.

Certain GSI projects had costs and stormwater mitigation capacities that were too large in relation to the rest of the data to be included in a linear-linear graph. These outliers are defined as data points whose cost and/or stormwater mitigation capacity was at least one order of magnitude greater than the next highest value. The use of a logarithmic scale to more easily display these outliers was avoided due to the fact that a logarithmic scale would make it more difficult to intuitively understand costs vs. mitigation capacities for the other data points, and a logarithmic scale would be more appropriate if the rest of the data was more evenly spread out over several orders of magnitude. Because there were only 3 large-value outliers out of 31 data points, the outliers were omitted for the sake of displaying more meaningful graphs. Instead, the equation of the best-fit line was included for each graph which would allow an individual to determine whether or not the cost of the outlier falls below the line for the specific stormwater mitigation capacity of the outlier.

A trendline was constructed for each graph that would best illustrate the data. An explanation for a specific trend line's shape is discussed at length with regard to its respective graph in **Section 5.0**. In all cases, the trendline is based off of the data points on the map and its shape would vary with the addition of new data points, as the trend line compared the data points to each other, rather than an independent standard. The trend line helps to point out outliers within the data so that they could be analyzed further to explain their behavior.

4.0 | Data

Name	Location	Avg. Precipitation (in/yr)	Mitigation %	Specific Depth Mitigated (in)	Area of BMP (sq.ft)	Area Managed (sq. ft)	# Trees Eq. Val.	Tree Intercept (gal/yr)	Total Capacity (gal/yr)	Type	Date Completed	Cost (dollars)	Adjusted Cost (2017 dollars)	Annual Cost (dollars)
Cira Green	Philadelphia	44.51	90%	2	52,272	31,221	18	9,804	789,629	Green Roof (intensive)	2016	2,600,000	2,662,400	52,000
Drexel Park	Philadelphia	44.51	99%	3.1	108,900	108,900	45	24,509	3,016,574	Park	2008	500,000	618,970	10,000
The High Line	New York City	43.17	83%	1	8,447,155	8,447,155	1500	792,380	189,513,712	Green Roof (intensive)	2009	187,300,000	226,431,806	3,746,000
Lea Elementary School	Philadelphia	44.51	81%	1	5,500	5,500	19	10,348	133,987	Porous Pavement	2016	490,000	501,760	9,800
Central Green	Philadelphia	44.51	99%	3.1	217,800	217,800	300	163,395	6,147,526	Park	2015	7,400,000	7,759,462	148,000
Lindwood Park	Ardmore, PA	46	99%	3.1	45,336	45,336	38	21,390	1,308,710	Park	2010	386,000	455,708	7,720
NYC Parks Green Roof	New York City	43.17	90%	1.4	30,233	30,233	10	5,283	737,696	Green Roof (intensive)	2010	370,000	436,819	7,400
Bronx River Houses	New York City	43.17	97%	2	7,900	37,220	2	1,057	972,865	Bioretention	2011			
Canarsie Parking Lot	New York City	43.17	99%	3.16	1,600	36,000	0	0	959,335	Bioretention	2012			
Far Rockaway Park and Ride	New York City	43.17	82%	0.95	12,990	20,320	1	528	449,036	Bioretention	2011			
Spring Creek Wet Meadow	New York City	43.17	100%	5	2,600	14,000	1	528	377,371	Bioretention	2011			
Metropolitan Ave Blue Roof	New York City	43.17	65%	0.5	21,820	21,820	0	0	381,769	Green Roof (extensive)	2011			
PS118 Green/Blue Roof	New York City	43.17	65%	0.5	7,000	7,000	1	528	123,002	Green Roof (intensive)	2011			
One Lincoln Plaza	New York City	43.17	93%	1.5	20,000	59,935	21	11,093	1,511,455	Green Roof (intensive)	2017			
The Hill Governor's Island	New York City	43.17	99%	3.16	3,789,720	3,789,720	2250	1,188,570	102,177,729	Park	2016	71,000,000	72,704,000	1,420,000
Franklin Square School	Baltimore	45.08	99%	3.16	58,806	58,806	7	3,861	1,640,268	Park	2010	115,000	135,768	2,300
Franklin Square Curb Ext	Baltimore	45.08	30%	1	700	107,157	2	1,103	904,703	Bioretention	2010	232,325	274,281	4,647
BioPark Café Terrace	Baltimore	45.08	99%	3.16	14,000	14,000	9	4,965	394,545	Park	2014	400,000	429,497	8,000
CPSC Park Master Plan	Gaithersburg, MD	42	99%	3.16	392,040	392,040	86	44,199	10,208,213	Park	2017	6,000,000	6,000,000	120,000
Greenbriar Local Park	Bethesda, MD	43	99%	3.16	370,260	370,260	104	54,722	9,882,624	Park	2016	3,570,948	3,656,651	71,419
John McCormack Fed	Boston	42.44	86%	1	11,323	11,323	1	519	258,202	Green Roof (extensive)	2011	169,845	195,818	3,397
Acme at Trolly House	Wilmington, DE	43.12	70%	0.8	9,000	17,000	25	13,191	333,137	Bioretention	2010	180,000	212,506	3,600
Central Wharf Plaza	Boston	42.44	94%	1.5	13,100	12,300	30	15,580	321,535	Park	2007	confidential		
KidZooU	Philadelphia	44.51	83%	1.1	19,332	82,120	120	65,358	1,956,983	Green Roof (intensive)/bioretention	2013	3,300,000	3,628,388	66,000
Kroc Center	Philadelphia	44.51	81%	1	335,412	566,280	30	16,340	12,746,217	Bioretention	2010	6,900,000	8,146,082	138,000
Lurie Garden	Chicago	37.93	60%	0.5	130,680	130,680	120	55,696	1,910,054	Green Roof (extensive)	2004	9,000,000	12,250,165	180,000
Palmisano Park	Chicago	37.93	99%	3.16	1,176,120	1,176,120	4	1,857	27,539,074	Park	2010	10,000,000	11,805,916	200,000
Phoenix Park Phase 1	Camden, NJ	41.15	99%	3.16	230,860	230,860	400	201,414	6,065,551	Park	2015	3,000,000	3,145,728	60,000
Shoemaker Green	Philadelphia	44.51	99%	3.16	119,790	119,790	22	11,982	3,303,254	Park/Bioretention	2012	8,500,000	9,570,149	170,000
Sidwell Friends Middle School	Washington, D.C.	40.93	89%	1.2	65,340	65,340	5	2,504	1,486,598	Bioretention	2007	4,000,000	5,070,602	80,000
Stroud Research Center	Avondale, PA	47	97%	2.5	142,005	142,005	55	31,632	4,068,305	Bioretention	2012	5,600,000	6,305,039	112,000
U.S. Coast Guard Headquarters	Washington, D.C.	40.93	96%	1.7	1,393,920	1,393,920	240	120,202	34,271,029	Green Roof (intensive)/bioretention	2013	28,900,000	31,775,886	578,000
Washington Canal Park	Washington, D.C.	40.93	89%	1.2	130,680	130,680	300	150,253	3,118,440	Bioretention	2012	20,000,000	22,517,998	400,000
Milliman Zhu Residence	Boston	42.44	86%	1	1,800	2,000	1	519	46,034	Green Roof (extensive)	2004	10,000	13,611	200
Tower Building MassArt	Boston	42.44	86%	1	750	1,000	2	1,039	23,796	Green Roof (extensive)	2006	15,150	19,666	303
18th Street Residence	New York City	43.17	83%	1	435	500	0	0	11,171	Green Roof (extensive)	2005	6,960	9,251	139
2nd Street Residence	New York City	43.17	83%	1	400	1,200	1	528	27,338	Green Roof (extensive)	2005	5200	6,912	104
Cook+Fox Architects LLp	New York City	43.17	83%	1	3600	19,000	4	2,113	426,600	Green Roof (extensive)	2006	46,800	60,750	936
Free Library of Philadelphia	Philadelphia	44.51	86%	1	5000	29,424	1	545	702,821	Green Roof (extensive)	2008	200,000	247,588	4,000
Friends Center	Philadelphia	44.51	86%	1	10000	13,046	0	0	311,375	Green Roof (extensive)	2007	500,000	633,825	10,000
Nationals Park	Washington, D.C.	40.93	84%	1	6317	24,710	0	0	529,717	Green Roof (extensive)	2008	100,000	123,794	2,000

Figure 5: The main data table which includes the complete parameters of each GSI project analyzed and will be used as the basis for all other data analysis. Blank cells indicate missing data that could not be acquired. Table has not been modified in aspect ratio.

New York City:

Annual Precipitation New York City (in.)	**43.17**
% of Precipitation Events Under 1-in	**87.4%**
% of Precipitation Events Under 1.5-in	**94.6%**
Vol. Portion of Prcp under 1-in Mit	**0.83**
Vol. Portion of Prcp under 1.5-in Mit	**0.93**

Philadelphia:

Annual Precipitation Philadelphia (in.)	**44.52**
% of Precipitation Events Under 1-in	**87.0%**
% of Precipitation Events Under 1.5-in	**93.9%**
Vol. Portion of Prcp under 1-in Mit	**0.81**
Vol. Portion of Prcp under 1.5-in Mit	**0.90**

Boston:

Annual Precipitation Boston (in.)	**42.45**
% of Precipitation Events Under 1-in	**89.9%**
% of Precipitation Events Under 1.5-in	**96.0%**
Vol. Portion of Prcp under 1-in Mit	**0.86**
Vol. Portion of Prcp under 1.5-in Mit	**0.94**

Baltimore:

Annual Precipitation Baltimore (in.)	**45.09**
% of Precipitation Events Under 1-in	**87.6%**
% of Precipitation Events Under 1.5-in	**93.5%**
Vol. Portion of Prcp under 1-in Mit	**0.81**
Vol. Portion of Prcp under 1.5-in Mit	**0.90**

Washington D.C.:

Annual Precipitation Washington D.C. (in.)	**40.93**
% of Precipitation Events Under 1-in	**88.7%**
% of Precipitation Events Under 1.5-in	**95.4%**
Vol. Portion of Prcp under 1-in Mit	**0.84**
Vol. Portion of Prcp under 1.5-in Mit	**0.93**

Pittsburgh:

Annual Precipitation Pittsburgh (in.)	**39.32**
% of Precipitation Events Under 1-in	**93.9%**
% of Precipitation Events Under 1.5-in	**98.7%**
Vol. Portion of Prcp under 1-in Mit	**0.93**
Vol. Portion of Prcp under 1.5-in Mit	**0.97**

Chicago:

Annual Precipitation Chicago (in.)	**37.13**
% of Precipitation Events Under 1-in	**91.1%**
% of Precipitation Events Under 1.5-in	**97.0%**
Vol. Portion of Prcp under 1-in Mit	**0.86**
Vol. Portion of Prcp under 1.5-in Mit	**0.93**

Figure 6: Precipitation data for New York City, Philadelphia, Boston, Baltimore, Washington D.C., Pittsburgh, Chicago. Vol. Portion of Prcp is a coefficient value, multiply by 100 for equivalent percentage. Vol. Portion of Prcp translates to Mitigation % in Figure 5 depending on the Specific Depth Mitigated (in).

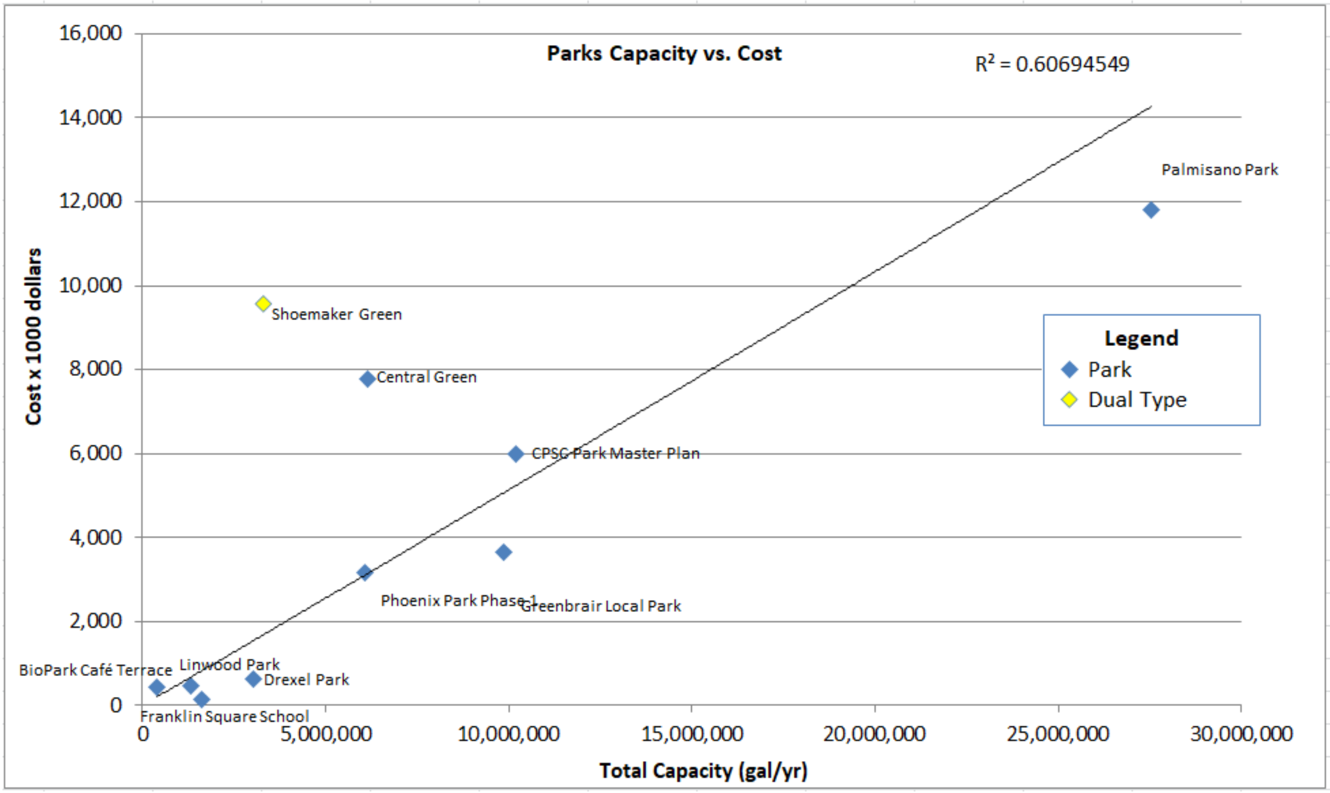


Figure 7: A graph comparing the total mitigation capacity of parks in gallons per year to their cost. The High Line and The Hill at Governor's Island were omitted from this graph due to their very large size and cost which would cause graphical distortion.

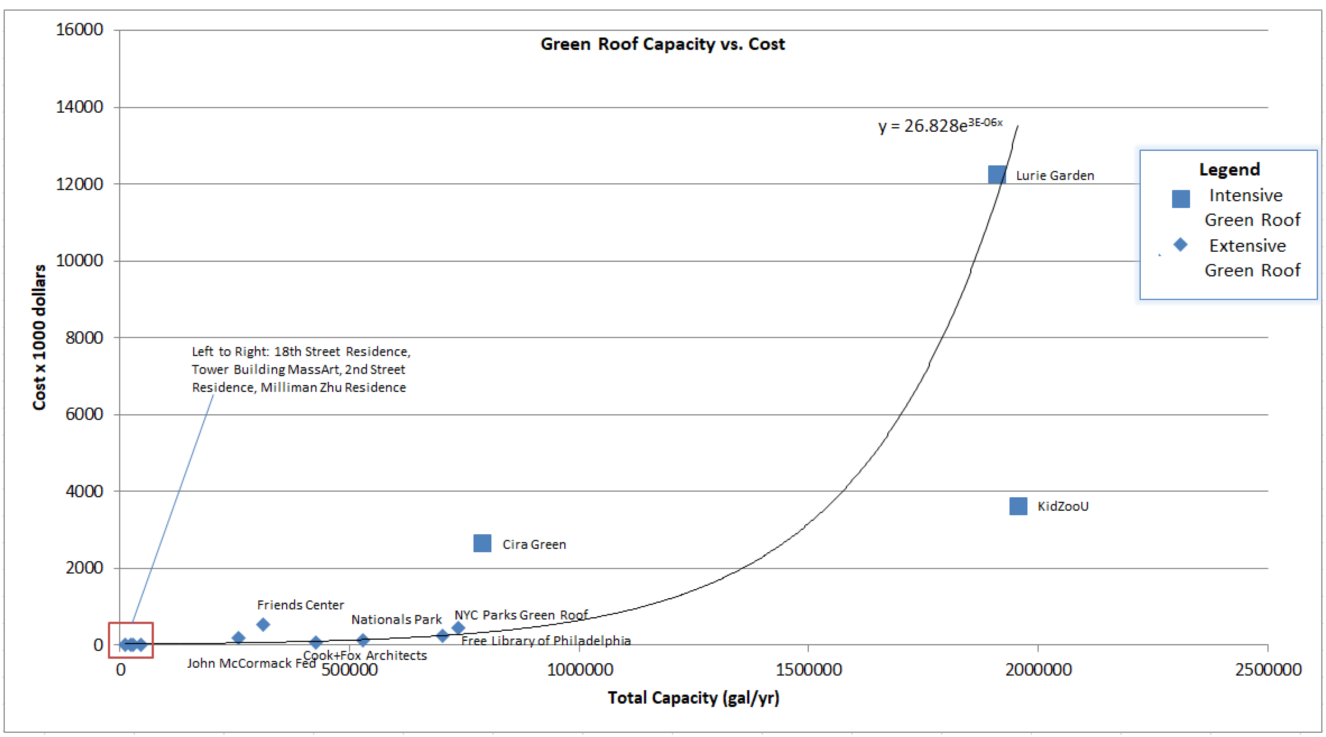


Figure 8: A graph comparing the total mitigation capacity of green roofs in gallons per year to their cost. U.S. Coast Guard Headquarters was omitted from this graph due to its very large size and cost which would cause graphical distortion.

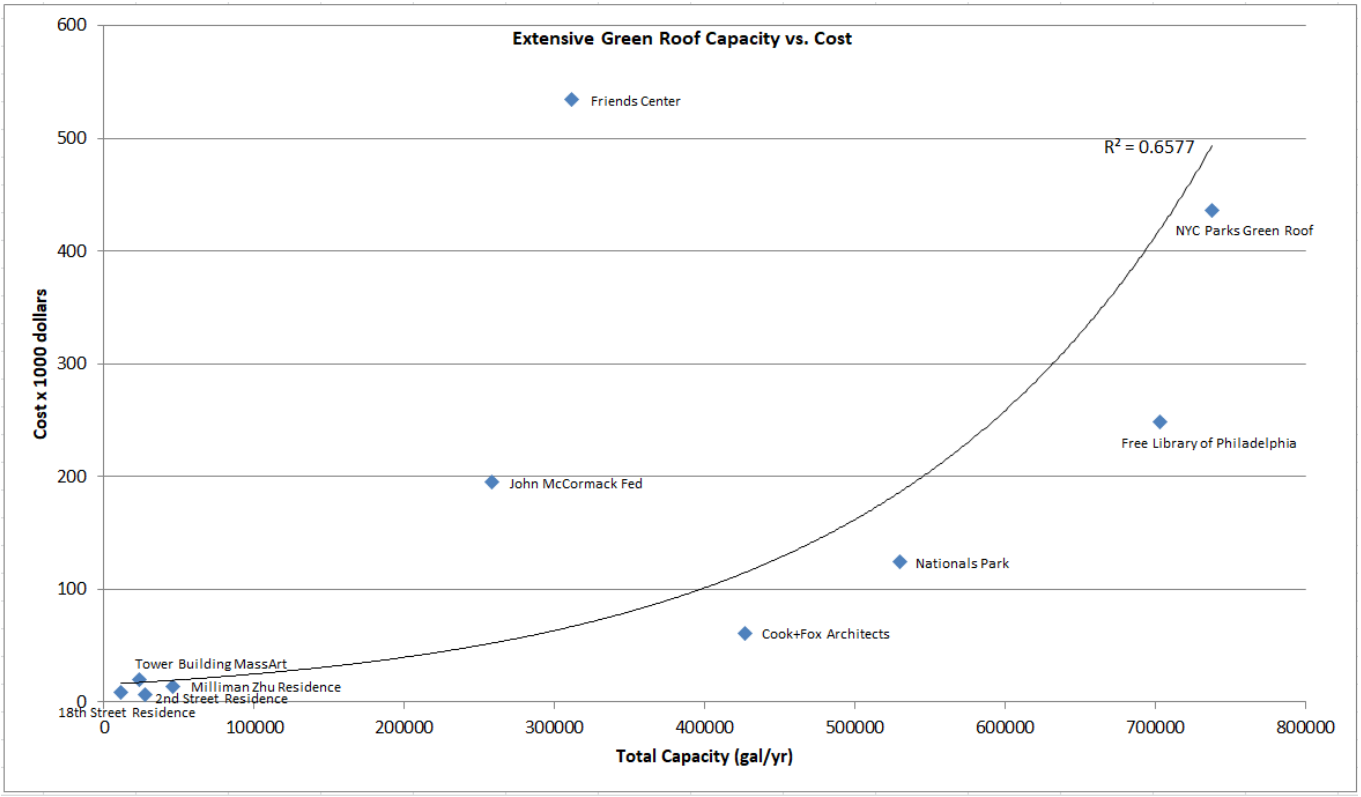


Figure 9: A graph comparing the total mitigation capacity of only extensive green roofs in gallons/year to their cost.

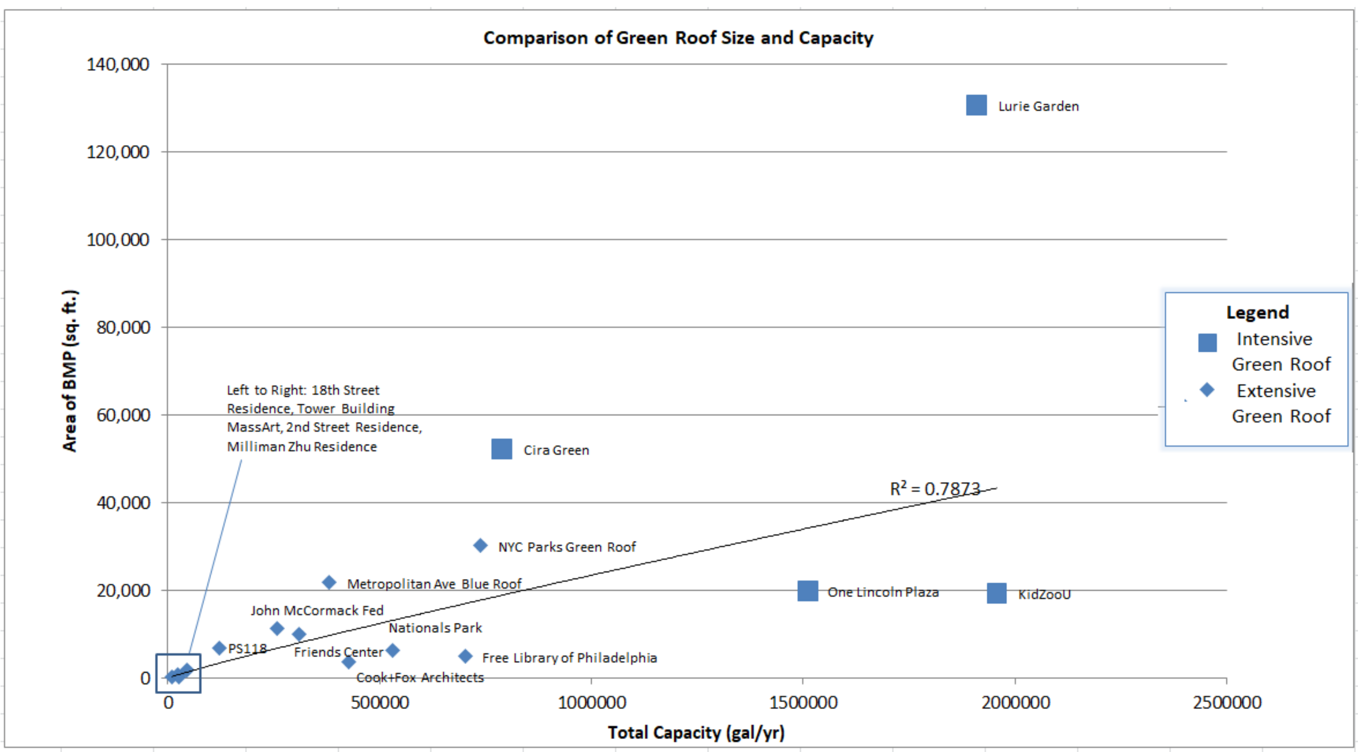


Figure 10: A graph comparing the total mitigation capacity of green roofs in gallons per year to their size in square feet.

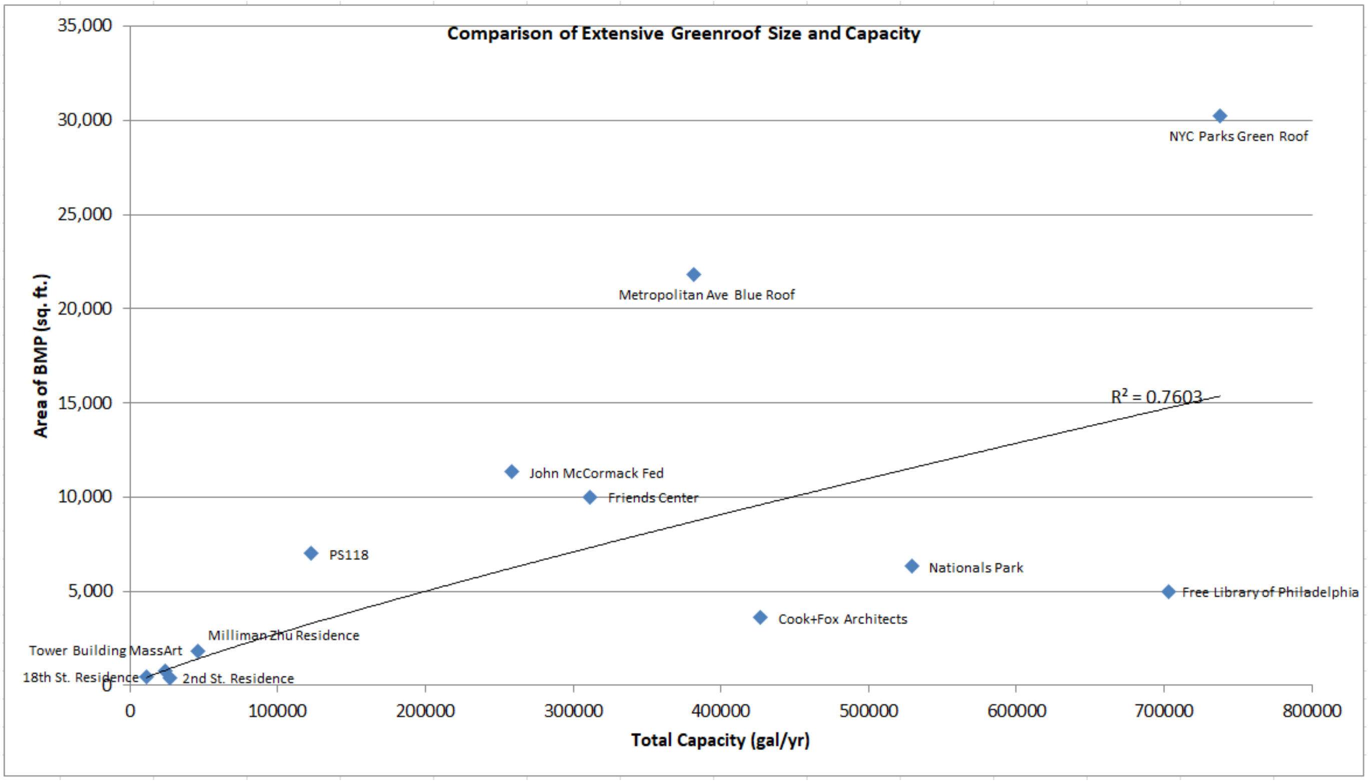


Figure 11: A graph comparing the total mitigation capacity in gallons per year of only extensive green roofs to their size in square feet.

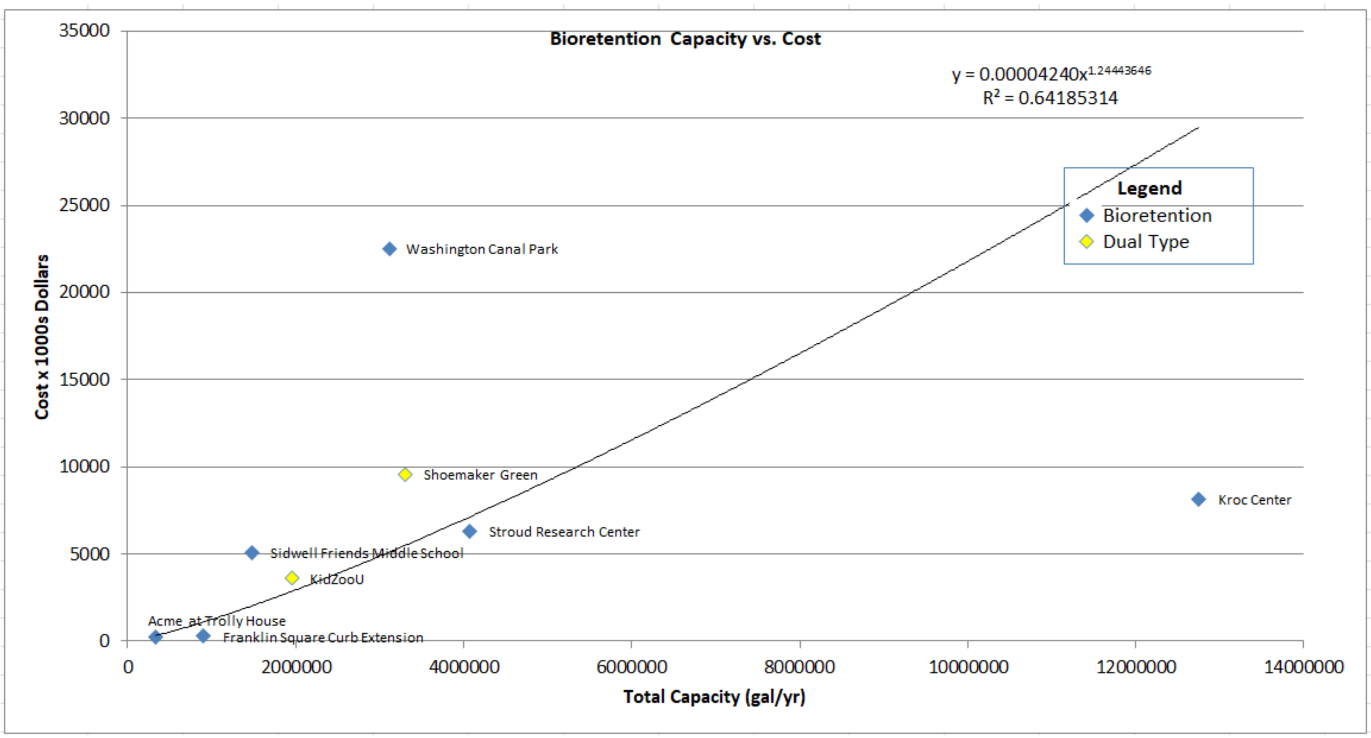


Figure 12: A graph comparing the total mitigation capacity in gallons per year of bioretention BMPs to their cost. U.S. Coast Guard Headquarters was omitted from the graph due to its large size and cost.

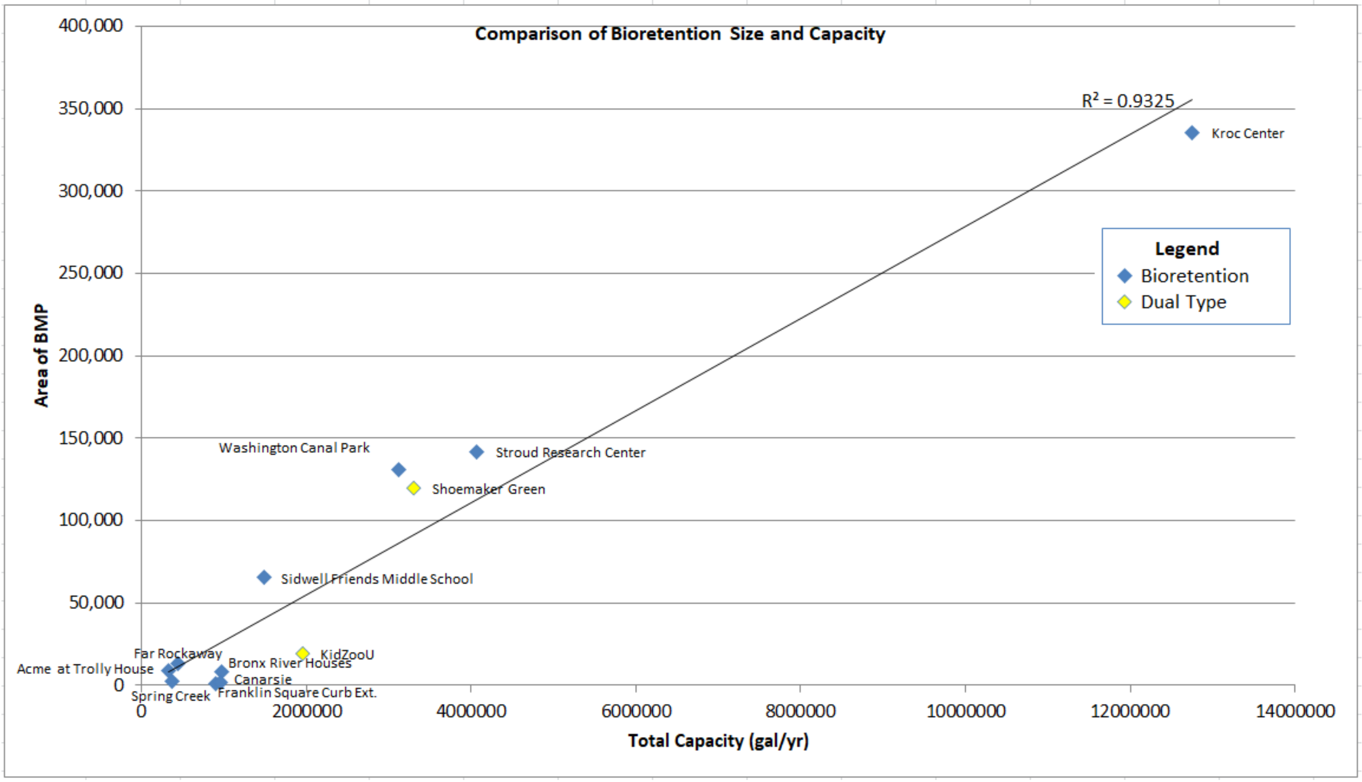


Figure 13: A graph comparing the total mitigation capacity in gallons per year of bioretention BMPs to their size in square feet. U.S. Coast Guard Headquarters was omitted from the graph due to its large size and cost.

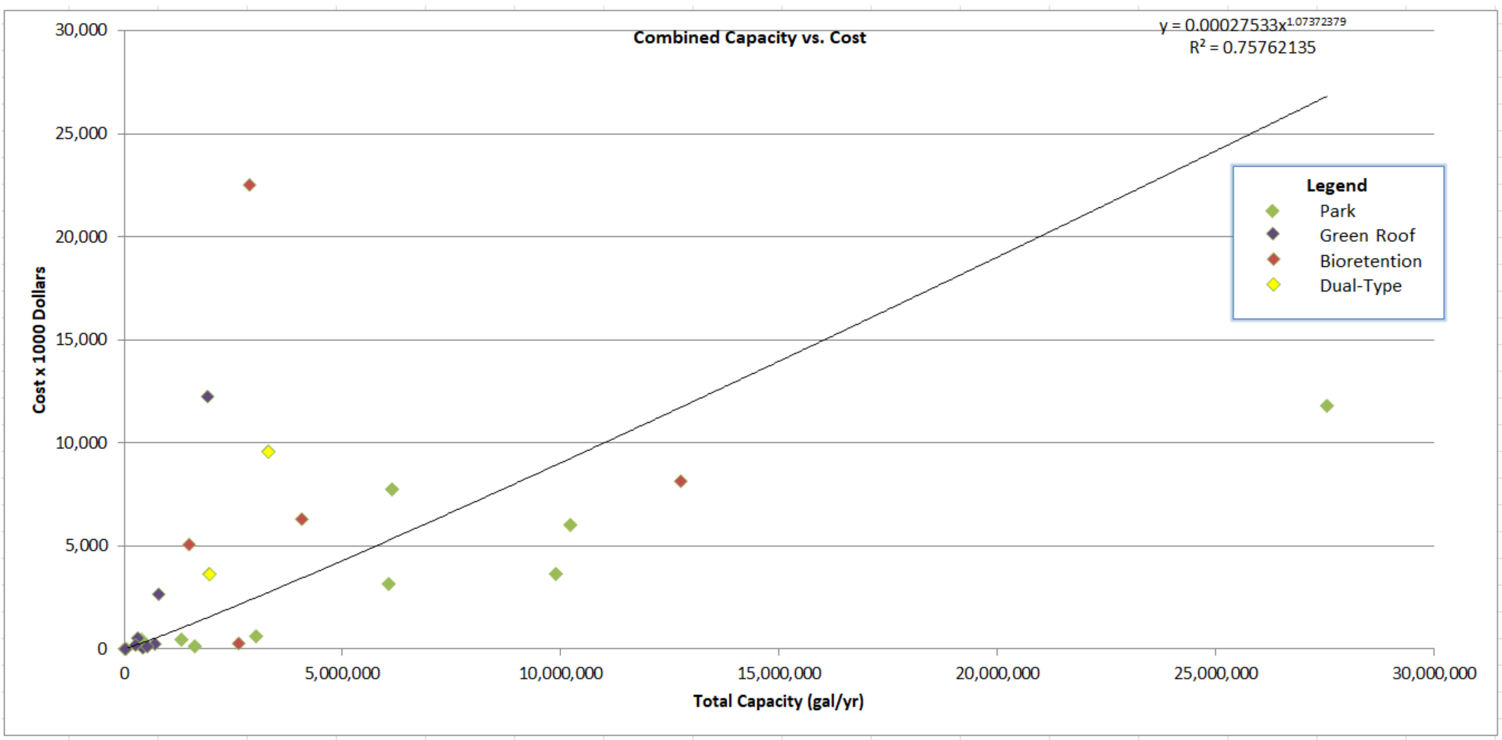


Figure 14: A graph comparing the total mitigation capacity in gallons per year of all GSI projects that were graphically analyzed regardless of type, to their cost.

5.0 | Discussion

Graphically analyzing the differences between individual GSI projects is an important step in understanding why some GSI projects are more efficient at mitigating stormwater than others while other GSI projects are more effective at accomplishing other goals, such as providing spaces for recreation or adding property value to real estate, as well opening the possibility of other conclusions that could be drawn when analyzing data that has not been previously placed on a graph.

Parks

Figure 7 compares the total mitigation capacity of parks in gallons per year to their cost. A linear, best fit trend line is drawn through the datapoints used to illustrate the differences between certain datapoints, and shows an R^2-value of 0.601. Based on where the datapoints fall along the trend line, it becomes apparent that certain parks are more efficient at mitigating stormwater than others relative to their cost. The most efficient of these parks appears to be the Franklin Square playground which is able to mitigate almost 1.62 million gallons of stormwater annually despite a cost of $135,000. Franklin Square playground's development costs consisted of entirely removing the asphalt from an already existing playground and planting grass and trees into the soil that was underneath the asphalt[24].

From the development standpoint, this is as simple as it one can get. The applications of such an approach are limited to projects of a relatively small area, and entirely impermeable recreational spaces that would serve the same purpose if they had permeable concrete pavement or grass. In urban settings, such locations are relatively commonplace, such as basketball courts, tennis courts, large multi-purpose asphalt-covered recreational areas at playgrounds and parking lots. It could be concluded that the low cost of depaving urban areas makes this an attractive approach to managing large volumes of stormwater efficiently, especially in low-income areas where other types of projects may prove prohibitavely expensive.

At the intermediate cost range for parks in **Figure 7** are parks such as Lindwood Park, Drexel Park, Phoenix Park Phase 1 and Greenbrair Local Park. These parks have the appearance and function of standard modern parks, complete with walkways, benches, trees and grassy areas for recreation. The cost of these parks significantly exceeds that of depaving projects such as Franklin School playground due to additional design costs and infrastructure installations, however they are not as limited by area as a depaving project would be, and their larger area allows for much more stormwater mitigation.

The high-cost, low stormwater mitigation efficiency range for parks in **Figure 7** would apply to heavily engineered GSI projects such as Shoemaker Green or Central Green. These parks tend to come with high design costs from landscape architecture and engineering firms and have a strong design focus on the aesthetics of the park in addition to the stormwater mitigation capabilities[43]. Shoemaker Green utilizes technology that is not typically found in parks, such as underground cisterns that significantly add to the cost of the project[44]. The high design costs of these parks adds to the overall cost of the GSI project and as a result, makes it less efficient at mitigating stormwater than a cheaper project, but it would be incorrect to conclude that such projects should be avoided in lieu of cheaper, more efficient ones. It is up to the developer of such a project to determine if the high-costs of the project would be a worthwhile investment in areas unrelated to stormwater such as increasing the property values of the surrounding area or if the project has to be of a very high quality to uphold a certain standard of the property owner. Shoemaker Green is owned by the University of Pennsylvania and is advertised as a technologically advanced stormwater control system, a description which brings significant value to its owner.

Green Roofs

Figure 8 compares the total mitigation capacity of green roofs (intensive and extensive) in gallons per year to their cost. A exponential best fit trend line was used for this data for two reasons:

1) The exponential trendline fits the data more accurately than a linear trendline (R^2 value of 0.7653 for exponential vs. 0.6345 for linear) suggesting that there may be an exponential relationship between the total capacity of a green roof and its cost and

2) A compelling argument could be made for the use of an exponential trendline as green roofs are three-dimensional GSI projects in that when they are limited in area by the roof that they are located on, the only way to increase stormwater mitigation capacity would be to build a thicker layer of substrate.

A thicker layer of substrate is not only more expensive to construct, but adds a large amount of additional weight to the roof both through the soil that it adds and the potential of the soil to hold more water during a storm event. The increase in both dead loads (soil and larger plants such as trees) and live loads (higher water content) requires additional reinforcement of the roof which significantly adds to the cost[35]. Parks and bioretention BMPs do not need to take these factors into account as the soil depth is generally not a limiting factor with regard to stormwater mitigation capacity for them and the weight of the project is irrelevant. The multiple additional compounding factors required to take into account when increasing the stormwater mitigation capacity of a green roof suggest that an exponential curve is needed to more accurately model the relationship between stormwater mitigation capacity and cost.

Intensive green roofs cost significantly more than extensive green roofs per square foot ($25-40+/sq.ft. vs. $9-25/sq.ft. respectively[47]) however the position of the intensive green roof data points in **Figure 8** in relation to the exponential trendline suggests that the exponential increase in cost hypothesis is not false. As with parks, the cost of green roofs could be highly variable based on how advanced the technology employed would be and how important aesthetics and design is to the owner. Cira Green is one such example of an extensive green roof that uses 'pancake cisterns' (flat and wide cisterns) to store stormwater that is used to water the plants[7]. Additionally, Cira Green is located on top of a parking garage that is nestled between a luxury residential high rise and a new, mixed-use skyscraper in one of the highest value areas in Philadelphia, implying that aesthetics and design played no small role in the design of Cira Green in such a well-trafficked and high profile area. KidZooU is one intensive green roof that is located in the Philadelphia Zoo and was constructed at a cost that was significantly lower than what the trendline predicts it should have cost. This is explained by the fact that KidZooU uses a hybrid green roof and bioretention stormwater management system that would give it increased stormwater mitigation capacity without incurring the additional costs of reinforcing rooftops and creating very thick substrate layers that were hypothesized in the previous paragraph to exponentially increase green roof costs at higher levels of stormwater mitigation.

Figure 9 compares the total mitigation capacity of only extensive green roofs in gallons per year to their cost. The line was kept exponential as it shows a better correlation to the data than a linear relationship (R^2 value of 0.6577 for exponential vs. 0.2299 for linear) and the same justification for the use of an exponential line applies. While extensive green roofs do not have substrate layers nearly as thick as intensive green roofs, the thickness of the substrate layer can range from 3 to 6 inches and resultant weight of the roof could be twice as large per square foot as a result[34]. The biggest outlier in **Figure 9** is Friends Center, which is significantly more expensive than its stormwater mitigation capacity would suggest, however this is easily explained by the developer installing additional services to the green roof that do not effect stormwater mitigation capacity such as geothermal wells to assist with heating and cooling[45]. Had the developer not installed the geothermal wells, the green roof at Friends Center was expected to be cheaper, however it is not clear by exactly how much.

Figure 10 compares the size of the green roofs in square feet to their stormwater mitigation capacity. Green roofs that were missing cost data and were omitted from **Figure 9** were added to **Figure 10** since the cost of the green roof is not a parameter for this graph. The actual area of the BMP is being compared to the stormwater mitigation capacity and not the Area Managed. Area Managed is an internal characteristic of the BMP that is used as part of the calculation to derive the total stormwater mitigation capacity while the Area of BMP is simply the green roof's footprint.

The purpose of this comparison is to determine if a more advanced or higher substrate depth green roof could be observed from the data to increase stormwater mitigation capacity of the roof without significantly increasing its footprint. Good adherence to the trendline would indicate that green roofs that use more advanced technology or thicker substrates, despite their costs, would be better at mitigating stormwater given the size constraints of green roofs in general. A fairly good R^2 of 0.7873 could be observed in **Figure 10** indicating that there is some adherence to the trend line. However, there are some surprising outliers present such as Lurie Garden and Cira Green which, as intensive green roofs, were expected to fall below the trendline rather than above it. A possible explanation for this would be either inaccurate data with regard to how much area these green roofs actually manage (which would significantly increase their stormwater mitigation capacity and move them closer to the trendline) or that the deep substrate in these green roofs is not being sufficiently saturated with water.

The supports that these green roofs are built on are designed to handle fully saturated soil with some factor of safety to spare, so underutilizing the capacity of the substrate to hold water would be a flaw in the green roof's design. As was discussed earlier, the cost of a green roof is expected to increase exponentially when increasing the area of the green roof, so while constructing a GSI project with underutilized capacity is a waste of money, constructing a green roof with the same problem is even more the case. A thinner substrate layer would be cheaper, require less maintenance and require less reinforcement of the green roof without affecting the green roof's stormwater mitigation capacity. Since most of that cost cannot be recouped if a developer realizes that a green roof (or any GSI project) is indeed underutilized, solutions to this concern would be to build a drainage system if possible that brings more stormwater to the green roof thereby increasing its area managed.

Figure 11 compares the size of only extensive green roofs in square feet to their stormwater mitigation capacity. The R^2-value is fairly good at 0.7603 but there are still two significant outliers: the Metropolitan Ave Blue Roof and the NYC Parks Green Roof. Both roofs were monitored by the New York City Department of Environmental Protection so their data is assumed to be accurate. The PS118 green roof was monitored by the same organization and shows a closer relationship to the trendline. Several possible explanations could exist for these results, including an underutilization of the roof during the monitoring year, malfunction of one or more systems on these two roofs resulting in a lower than expected stormwater mitigation capacity, or an overestimation of stormwater mitigation capacity of other data points on the graph causing the trendline to be unusually distant from the Metropolitan Ave Blue Roof and NYC Parks Green Roof data points.

Bioretention

Figure 12 compares the total stormwater mitigation capacity in gallons per year of bioretention GSI projects to their cost. A linear trend line to model the data was initially used but due to significant outliers such as Washington Canal Park, Acme at Trolly House and Franklin Square Curb Extension, the R^2-value of a linear trend line was exceedingly low. Several different trendline types were attempted to determine which one could describe the data best. Using an exponential trendline to model the data produced the highest R^2-value of 0.64 of any other method while still leaving two significant outliers, specifically Washington Canal Park and Kroc Center.

Washington Canal Park, despite the name, more closely resembles a bioretention BMP in design and function. It's $20 million cost[7] is significantly higher than anything in its class (even Shoemaker Green which is considered very expensive is less than half the price for superior stormwater capacity) which suggests that there may have been externalities such as issues with design and implementation which may have increased the cost. Washington Canal

Park has an ambitious design, using technology not commonly employed in bioretention BMPs such as an advanced irrigation system, multiple cisterns and a microfiltration/ultraviolet water treatment system[7](**Figure 15**), however these additions alone would not explain the high cost. A microfiltration/ultraviolet water treatment system can range from $450,000 for a small, high-end system to as much as $25 million for a commercial scale water treatment facility[46], but the system used at Washington Canal Park more closely resembles a smaller model in terms of capacity.

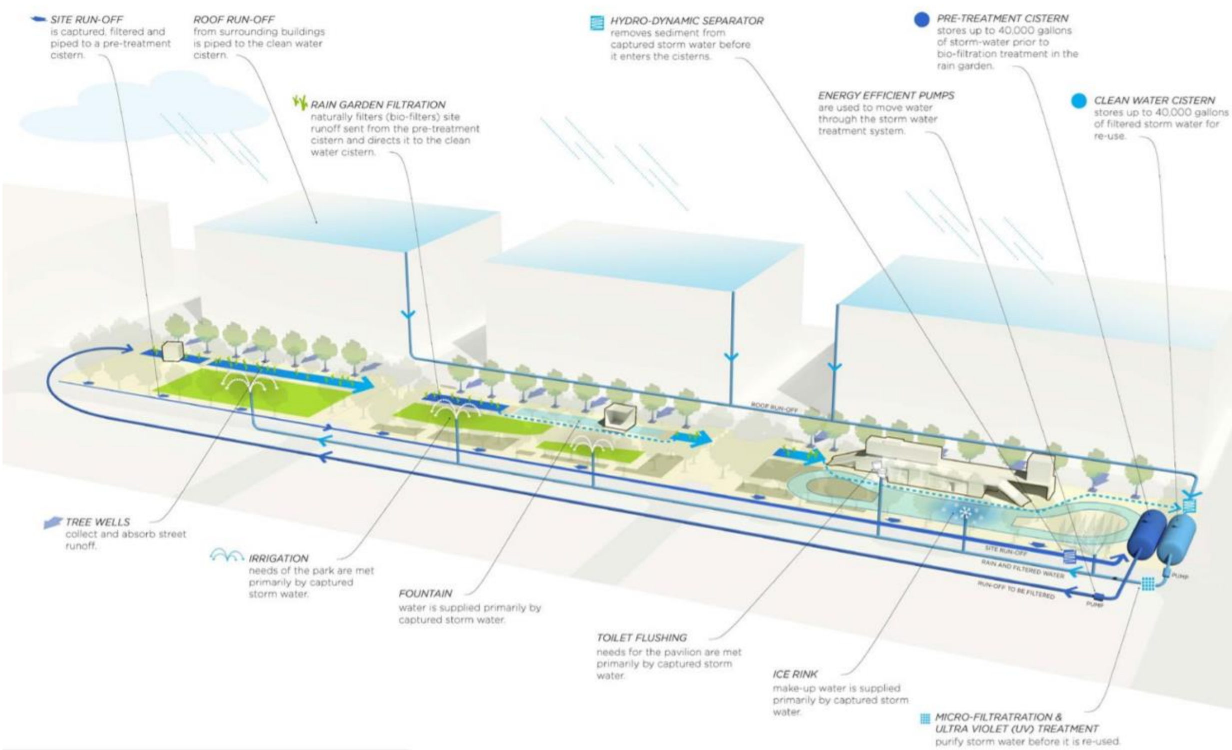


Figure 15: An illustration of the stormwater system at Washington Canal Park. Source: (GSI Partners Flipbook[7])

The shape of the trend line in **Figure 12** suggests that bioretention BMPs get marginally more expensive as their stormwater mitigation capacity increases. Bioretention BMPs are not subject to the strict area constraints of green roofs, but they are also more functional in design than parks. As the size of a bioretention basin grows, there is an increased necessity to construct walkways and other areas for human use. The smallest bioretention BMPs such as ACME at Trolly House can get away with being little more than a hole in the ground that funnels in stormwater for retention, however larger bioretention BMPs such as Washington Canal Park or Shoemaker Green need to create areas for human use. Kroc Center actually demonstrates this concept well, as it can mitigate 12.75 million gallons of stormwater annually at a price of only $6.9 million. The design of Kroc Center (in **Figure 16** and **Figure 17**) shows its extremely practical design in relation to the design of Washington Canal Park in **Figure 15**, essentially acting as a large depression with few facilities designed for purposes other than stormwater mitigation.

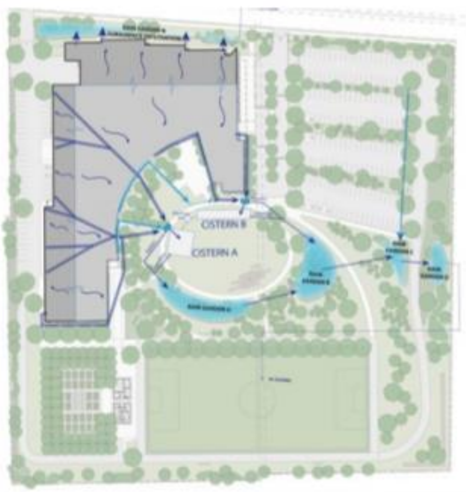


Figure 16 (top): A profile illustration of Kroc Center, showing the various sections and functions of this bioretention BMP. Source: (GSI Partners Flipbook[7])

Figure 17 (left): An aerial illustration of Kroc Center. Arrows indicate direction of stormwater runoff. Source: (GSI Partners Flipbook[7])

Figure 13 compares the size of bioretention BMPs in square feet to their stormwater mitigation capacity. A strong correlation between total stormwater mitigation capacity and area of BMP can be observed with an R^2-value of 0.9325. There are no significant outliers in this graph when the cost is taken out of the equation. Possible variations in stormwater mitigation capacity could be attributed to the topography around the bioretention BMP influencing the rates at which it can capture stormwater or under-utilization.

<u>Combined</u>

Figure 14 compares the stormwater mitigation capacity of all GSI projects used in the analysis to their cost. Previously in this analysis, GSI projects were only compared to other projects within their own type. This graph was constructed simply to determine if any sort of general observations could be made about the relative relationships of different GSI projects to cost and stormwater mitigation capacity. It can be observed from **Figure 14** that green roofs tend to cluster more around the low-cost, low-capacity range while other types of projects tend to be more variable in cost and capacity. Parks tend to appear below the trend line while bioretention BMPs tend to preferentially appear above the trendline suggesting that parks are more efficient at stormwater mitigation than bioretention BMPs for the price. These observations were made for the data points that were analyzed in **Figure 14**, which carries a significant degree of error as general observations such as determining which type of GSI project is more efficient than another type would require a much larger data set. Ultimately, each type of GSI project is useful for specific purposes and general observations cannot be applied to every situation, so it is up to the developers and city planners to decide what sort of GSI project would be optimal for their specific setting, budget and purposes.

5.1 | Error Analysis

Error 1: In a perfect world, every GSI project would be monitored and all relevant data regarding the GSI project would be recorded and publicly available in an expansive online database with a powerful array of search parameters available. The most significant source of error for this graphical analysis is the variable quality of the data. When a data point is lacking information, assumptions need to be applied and calculations need to be performed in order to fill in the missing pieces of data using other information that is available about the GSI project. Each time a characteristic of a GSI project has to be derived from internal and external characteristics that are available, assumptions about the behavior of the internal/external characteristics with regard to the derived characteristic must be made and the level of error for the resulting value increases. There will always be certain characteristics about GSI projects that need to be derived regardless of monitoring efforts, such as the stormwater mitigation capacity, but the reliability of these estimates would be significantly improved if monitoring efforts were increased and more reliable, site specific data could be obtained.

As a result of the generally poor quality and resolution of data available for GSI projects, a selection bias presents itself in the sense that only GSI projects that provided a sufficient amount of data were used in the analysis. In a hypothetical situation, if all GSI projects in the northeastern United States had monitored data that was publicly available, much clearer patterns would emerge from the graphical analysis of this data as selection bias would be minimized. In all cases, a larger sample size would be much more beneficial for data analysis because it would minimize the impact that various unforeseeable externalities have on the cost of a GSI project.

Error 2: A second source of error is misleading information about a GSI project from the sources that are provided. Unfortunately, some sources provide contradictory information about a characteristic of a GSI project. For example, one source states that the cost of the Cira Green greenroof is $12 million[47] while another source puts the cost at $2.6 million[7]. The difference in cost is large; however in this case, both costs were significantly higher than other green roofs with a similar stormwater mitigation capacity so the difference in cost is inconsequential would not have prevented Cira Green from becoming an outlier. This would not change the conclusion that a large portion of the money spent on Cira Green was devoted to design and aesthetics. For other GSI projects where the low-end cost estimate is close to its competitors, an overestimation of the cost by a factor of five could cause very different conclusions to be made about a GSI project's efficiency in relation to similar projects.

Error 3: A third source of error is the reliability of the source. This type of error is closely related to **Error 2** in that while there is precedent for different sources providing contradictory or unclear information, in many situations, there is only one source that has information available about a certain characteristic of a GSI project. If this source happens to be the developer that has intimate knowledge of the inner workings of their GSI project, a good degree of confidence could be established. Unfortunately, often this has not been the case, as developers rarely divulge enough technical information about a GSI project whether through personal contact or publicly available information online.

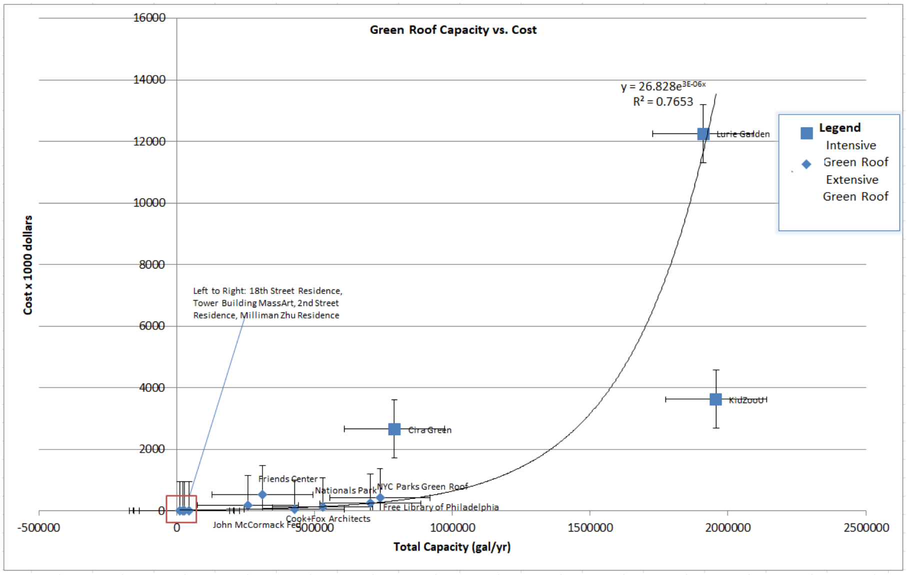
When data cannot be obtained from a developer, third-party sources and online databases are necessary, but it is difficult to know how they retrieved the data or whether they encountered the same issues. Even in situations where the developer does provide all of the necessary data, sometimes actual monitoring data could reveal information about the GSI project's stormwater mitigation capacity that the developer was not aware of. In some cases, the developer will provide a higher cost estimate for a GSI project by including features that are not related to stormwater mitigation, such as with Friends Center in Philadelphia and the construction of geothermal wells that are used for heating and cooling[45].

Error 4: A fourth source of error is the possibility of development mistakes being hidden within the cost of a GSI project. Events such as a conflict with the developer and owner, conflict with regulatory agencies, miscalculations with regard to the specifications of a GSI project, employee error, accidents and other externalities may have an effect on the cost of a GSI project that are entirely unrelated to its design and ability to mitigate stormwater. There is a certain degree of development errors that affect any infrastructure project and should therefore be accepted as cost-adding, foreseeable events however projects where these development errors are egregious should be looked at with additional scrutiny. If a GSI project has a cost that is unusually high, even when compared to projects are a similar size, using similar technology, and designs and have a similar capacity, serious development errors become a possible explanation for the cost increase. An example of a possible cost override is Washington Canal Park[7].

Error 5: Google Earth Pro was used to calculate the likely area managed of a GSI project in the absence of known area managed data. This method was applied to 7 data points within the entire analysis. The Google Earth Pro method used in this analysis involves drawing a polygon around the likely area managed of a GSI project based on a set of rules (fully described in **Section 3.1: Area Managed (sq.ft)**). This process is done by hand (shown in **Figure 2**) and is therefore somewhat variable; however the extent of error present in this process was controlled for by repeating the process with a slightly different set of assumptions to determine how they affect the area managed value. This does not mean that the error does not exist, but that it is not assumed to be so large as to change the possible conclusions that can be made about the GSI project.

Error 6: A possible error exists in the graphs themselves where, in the absence of outliers that exist both above and below the trendline, a significant outlier on one side of the trendline may have an unusually large effect on the position of the trendline. This effect would be minimized with an increase in data points. Trend lines were chosen based on whether they have a good adherence to the data and could be justified using physical principles relating to the type of GSI used. Due to this type of error, the actual slope and equation of the trendline is less important than the type of relationship that the trendline attempts to illustrate. Discretion was taken in identifying cases where a single outlier sets the pattern of the trendline to be different than it would otherwise be, however this was not the case for any of the figures. **Figure 8** and **Figure 9** show that even without the inclusion of Lurie Garden, the trendline still retains its characteristic shape.

As a result of the many types of possible errors present and the compounding effect that they may have on each other, it becomes difficult to provide specific numbers regarding the exact efficiency of each GSI project. That being said, a graphical approach shows clear patterns emerge when comparing GSI projects, even ones in a relatively small data set. The errors present are not expected to effectively disrupt these patterns.



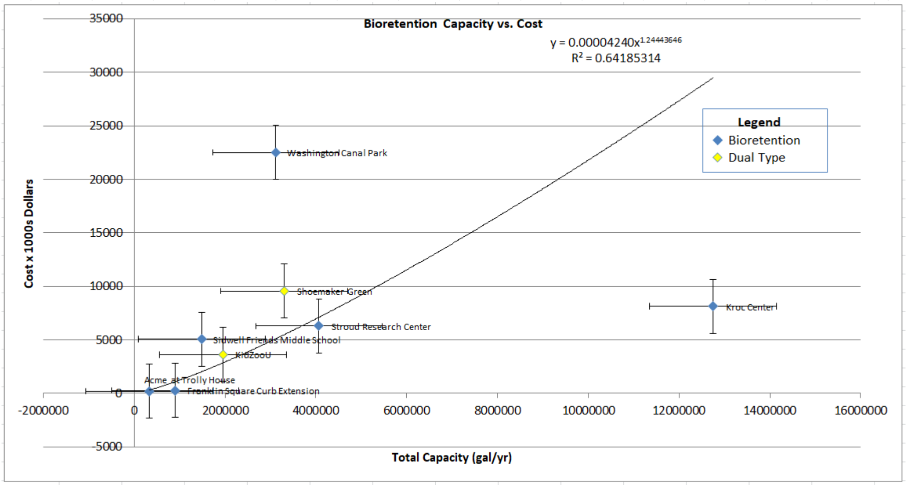


Figure 18(left-top): Same as Figure 8, but with standard error bars present.

Figure 19 (left-bottom): Same as Figure 9, but with standard error bars present.

Figure 18 and **Figure 19** demonstrate using standard error that the prevailing patterns in the graphs would not change significantly even with calculation errors involved. The calculation error described in **Error 5** as a result of Google Earth Pro is expected to be much smaller than what the error bars in **Figure 18** and **Figure 19** would suggest, as they show cost deviations in the order of many millions of dollars, and stormwater mitigation capacity deviations as high as 4 million gallons per year, which is highly unrealistic. The calculations used in this analysis to derive certain characteristics would not yield such large error bars as they are not empirical and are based on hydrologic principles, and the Google Earth Pro polygon method would not yield such large error bars as they would require an unrealistically large overestimate or underestimate of the area managed, which would not abide by the rules used in this method. The most serious source of error is likely to be potentially inaccurate data obtained from sources, as there is precedent for this from the contradictory Cira Green cost data ($12 million vs. $2.6 million). There is a possibility that inaccurate data could be coupled with inaccuracies in the derivation process itself to have a compounding effect and producing a data point that would fall outside of the error bars.

6.0 | Conclusion

When planning a future GSI development, one method of determining the cost and efficacy of the GSI project is by comparing it to similar, already existing GSI projects. However, this approach can be very qualitative in nature and would often be limited to the general features and appearance of the GSI project being used for comparison. If a developer desired to construct a 10,000 square foot extensive green roof to achieve a specific stormwater mitigation goal, they would look at other similarly-sized extensive green roofs. The next step would be to call a landscape architecture firm or a service that specializes in green roof installation and get an approximate quote of how much that type of project would cost. Even if the developer decides to “shop around”, this approach would still give the developer only a relatively small sample set of data that they could use to make their determination of which green roof is best, and it would make comparisons between similar projects both difficult and time-consuming.

A graphical approach to analysis of individual GSI project stormwater mitigation in urban settings would allow the developer to draw from a much larger set of data and be able to easily interpret the data so that they can make better informed decisions regarding the type of GSI project that is necessary for their stormwater mitigation needs. On a graph, the characteristics of the GSI projects become much more effective at representing relationships within a larger data set, demonstrating how GSI projects with certain characteristics cluster together based on their cost and stormwater mitigation capacity. A developer would be able to see which GSI projects were designed with purely stormwater management purposes in mind and which GSI projects had likely invested a lot of money into design and aesthetic purposes.

Additionally, this approach provides new forms of insight with regard to GSI projects that would not be apparent by simply looking at data that is not graphically displayed. For example, a developer could examine both the *stormwater mitigation capacity vs. cost*, and *stormwater mitigation capacity vs. area of BMP* graphs to make a determination of whether a GSI project has underutilized capacity. If a GSI project has a relatively high stormwater mitigation capacity despite having a small area compared to other projects, and shows that it is also relatively expensive compared to other projects with a similar stormwater mitigation capacity, it could suggest that such a project either has underutilized capacity. This does not mean that such an interpretation is necessarily correct for a specific project, as a GSI project could show the same pattern for other reasons, but it provides the developer with useful insight to inquire further. It would be very difficult to make the same determination without using a graphical approach.

The graphical approach provides a framework for comparing individual GSI projects on a larger scale. This report has demonstrated only two ways of comparing GSI projects: *stormwater mitigation capacity vs. cost* and *stormwater mitigation capacity vs. area of BMP*; and has shown clear patterns emerging that differentiate one project from another, as was illustrated in **Section 5.0**. The same method could be applied to comparing GSI projects using any other combination of project technical characteristics to come up with new interpretations. This method was only applied for stormwater mitigation, but it could be extended to other benefits from green infrastructure in general, such as carbon removed, or heat island effect reductions, especially in municipalities where stormwater runoff is not a concern. With a much larger data set, potential exists for using computer software to analyze the position of a specific GSI project on a graph in relation to similar GSI projects across many different criteria to draw even more sophisticated analyses about a project’s efficacy at mitigating stormwater.

The benefits of this method are not limited to assisting developers and designers in their decision making process. A more effective and quantitative way of understanding the benefits of GSI would help innovate the field as a whole by demystifying GSI stormwater mitigation efficiency. A greater focus on efficiency by developers who want to get the most out of their investment would provide the competition that is necessary to motivate innovators within the GSI field to develop new technology that would function better at mitigating stormwater for the cost. As with many other fields, data collection and analysis are the key elements required for continuing innovation and Green Stormwater Infrastructure is no different.

7.0 | Works Cited

1. "A Triple Bottom Line Assessment of Traditional and Green Infrastructure Options for Controlling CSO Events in Philadelphia's Watersheds." August 24, 2009. Accessed February 8, 2017. https://www.epa.gov/sites/production/files/2015-10/documents/gi_philadelphia_bottomline.pdf
2. "What We're Doing." Green City, Clean Waters | Philadelphia Water Department. Accessed December 17, 2017. http://www.phillywatersheds.org/what_were_doing/documents_and_data/cso_long_term_control_plan.
3. "Green Infrastructure Cost-Benefit Resources." EPA. October 14, 2016. Accessed February 08, 2017. https://www.epa.gov/green-infrastructure/green-infrastructure-cost-benefit-resources.
4. Romero, Melissa. "10 Green Projects in Philly You Should Know About." Curbed Philly. April 01, 2016. Accessed February 20, 2017. http://philly.curbed.com/2016/4/1/11346548/important-green-stormwater-infrastructure-projects.
5. "Green Stormwater Infrastructure Project Map." Green Stormwater Infrastructure Project Map | Philadelphia Water Department. Accessed February 17, 2017. http://www.phillywatersheds.org/BigGreenMap.
6. Economides, Christopher."Green Infrastructure: Sustainable solutions in 11 cities across the United States ." Spring 2014. Accessed February 2, 2017. http://water.columbia.edu/files/2014/04/Green_Infrastructure_FINAL.pdf.
7. Adams, Michele, Chelsea Fitzpatrick, Lauren Mandel, Melissa Muroff, Loretta Desvemine, Kate Farquhar, Steve Benz, and Jorce Lee. "Exceeding Intent: A Precedent Library of Exemplary Green Stormwater Infrastructure Projects ." December 2016. Accessed September 2017. http://gsipartners.sbnphiladelphia.org/wp-content/uploads/2014/07/flipbook.pdf.
8. University of Pennsylvania - Shoemaker Green » Andropogon Associates, Ltd. Accessed Feb 17, 2017. https://andropogon.com/work/academic/university-of-pennsylvania-2/.
9. "A Case Study on BMP's/LID at Penn's Shoemaker Green" Scavello, Grant, 2013, PDF
10. Green Roofs in Philadelphia, PA. Accessed February 17, 2017. http://www.greenroofworks.com/greenroofs.html.
11. "Your Water and Sewer Fees at Work." DEP Capital Projects. Accessed February 18, 2017. http://www.nyc.gov/html/dep/html/dep_projects/cp_fees_at_work.shtml.
12. "Your Water and Sewer Fees at Work." DEP Capital Projects. Accessed February 18, 2017. http://www.nyc.gov/html/dep/html/dep_projects/cp_fees_at_work.shtml.
13. "NYC Green Infrastructure Plan." 2012. Accessed December 17, 2017. http://www.nyc.gov/html/dep/pdf/green_infrastructure/2012_green_infrastructure_pilot_monitoring_report.pdf.
14. "The Economic Benefits of Green Infrastructure A Case Study of Lancaster, PA." Https://www.epa.gov/sites/production/files/2015-10/documents/cnt-lancaster-report-508_1.pdf. February 2014. Accessed February 8, 2017.
15. "Case Studies Analyzing the Economic Benefits of Low Impact Development and Green Infrastructure Programs." Https://www.epa.gov/sites/production/files/2015-10/documents/lid-
16. Parikh, Punam, Michael Taylor, Theresa Hoagland, and William Shuster. "At the Intersection of Hydrology, Economics and Law." Economic Incentives for Stormwater Control, 2011, 167-92. doi:10.1201/b11071-9.
17. Matthews, J.H. and T. Le Quesne, 2009: Adapting Water Management: A Primer on Coping with Climate Change. WWF Water Security Series 3. Surrey, World Wide Fund for Nature. http://www.worldwildlife.org/ climate/Publications/WWFBinaryitem12534.pdf
18. Abellán, Javier (2017). "Water supply and sanitation services in modern Europe: developments in 19th-20th centuries". 12th International Congress of the Spanish Association of Economic History: University of Salamanca, Spain.
19. "FAQ." FAQ | Philadelphia Water Department. Accessed December 17, 2017. http://phillywatersheds.org/watershed_issues/stormwater_management/faq.

20. Antje Stokman. "Water purificative landscapes–constructed ecologies and contemporary urbanism." Academia.edu - Share research. 2008. Accessed February 08, 2017. http://www.academia.edu/2369268/Water_purificative_landscapes_constructed_ecologies_and_contemporary_urbanism.
21. "The Economics of Green Infrastructure". Washington, D.C.: U.S. Environmental Protection Agency (EPA). 2015-11-02.
22. National Centers for Environmental Information (NCEI). "Climate Data Online." Climate Data Online (CDO) | National Climatic Data Center (NCDC). Accessed December 17, 2017. https://www.ncdc.noaa.gov/cdo-web/.
23. McMahon, Tim. "InflationData.com." US Inflation Long Term Average. April 01, 2014. Accessed December 17, 2017. https://inflationdata.com/Inflation/Inflation_Rate/Long_Term_Inflation.asp.
24. Hager, Guy. "Baltimore and Green Infrastructure." Accessed August 2017. http://www.mde.state.md.us/programs/Marylander/outreach/Documents/2.%20ParksandPlanning_Wter%20Quality%20Projects%20Completed.pdf.
25. "Green Roof." Mark K Morrison. Accessed December 17, 2017. http://www.markkmorrison.com/greenroof/.
26. "The Value of Green Infrastructure: A Guide to Recognizing Its Economic, Environmental and Social Benefits" (PDF). Chicago, IL: Center for Neighborhood Technology. 21 January 2011 http://www.cnt.org/publications/the-value-of-green-infrastructure-a-guide-to-recognizing-its-economic-environmental-and
27. Venkatraman, Kartik, and Nanjappa Ashwath. "Canopy Rainfall Intercepted by Nineteen Tree Species Grown on a Phytocapped Landfill." OMICS International. March 21, 2016. Accessed December 17, 2017. https://www.omicsonline.org/open-access/canopy-rainfall-intercepted-by-nineteen-tree-species-grown-on-aphytocapped-landfill-2252-5211-1000202.php?aid=69954.
28. VanWoert, N. D., D. B. Rowe, J. A. Andresen, C. L. Rugh, R. T. Fernandez, and L. Xiao. "Green roof stormwater retention: effects of roof surface, slope, and media depth." Journal of environmental quality. May 11, 2005. Accessed December 17, 2017. https://www.ncbi.nlm.nih.gov/pubmed/15888889.
29. Data, US Climate. "Temperature - Precipitation - Sunshine - Snowfall." Climate New York - temperature, rainfall and average. Accessed December 17, 2017. https://www.usclimatedata.com/climate/new-york/united-states/3202.
30. "Design Storm." UNESCO Gloss - VICAIRE - Module 1B - Chapter 2. Accessed December 17, 2017. http://echo2.epfl.ch/VICAIRE/mod_1b/chapt_2/main.htm.
31. "A Guide to Assessing Green Infrastructure Costs and Benefits for Flood Reduction." National Oceanic and Atmospheric Administration Office for Coastal Management. 2015. Accessed October 2017. https://coast.noaa.gov/data/digitalcoast/pdf/gi-cost-benefit.pdf.
32. "Rational Method Runoff Coefficient Tables for Storm Water Runoff Calculation." Brighthub Engineering. November 06, 2010. Accessed December 17, 2017. http://www.brighthubengineering.com/hydraulics-civil-engineering/93173-runoff-coefficients-for-use-in-rational-method-calculations/.
33. Txchnologist. "Going Against the Flow: Green Tech, Sensors and Industrial Internet Make Sewer Systems Smart." Txchnologist. May 13, 2013. Accessed December 2017. http://txchnologist.com/post/50336951628/going-against-the-flow-green-tech-sensors-and.
34. "Green Roof Types." Types of Green Roofs and Eco Roofs: Extensive and Intensive. Accessed December 2017. http://www.greenrooftechnology.com/green-roof-types.
35. "Greenroof FAQ." FAQ's. Accessed December 2017. http://www.greenroofs.com/Greenroofs101/faqs.htm.
36. "Sustainable Facilities Tool General Services Administration." System Overview > HVAC - GSA Sustainable Facilites Tool. Accessed December 2017. https://sftool.gov/explore/green-building/section/9/hvac/system-overview.
37. "Stormwater Technology Factsheet: Bioretention." EPA. 1999. Accessed December 2017.
38. "Using Trees and Vegetation to Reduce Heat Islands." EPA. August 12, 2016. Accessed December 2017. https://www.epa.gov/heat-islands/using-trees-and-vegetation-reduce-heat-islands.

39. "Stormwater Bumpout." Stormwater Bumpout | Philadelphia Water Department. Accessed December 2017. http://www.phillywatersheds.org/what_were_doing/green_infrastructure/tools/stormwater_bumpout.
40. Greenroofs.com: the greenroof & wall industry resource portal. Accessed December 2017. http://www.greenroofs.com/.
41. "The Importance of Operation and Maintenance for the Long Term Success of Green Infrastructure." EPA. April 2015. Accessed November 2017. https://www.epa.gov/sites/production/files/2015-04/documents/green_infrastructure-om_report.pdf.
42. Lampe et al (2005). Performance and Whole-Life Costs of Best Management Practices and Sustainable Urban Drainage Systems. Water Environment Research Foundation
43. "Navy Yards Central Green." Field Operations - project_details. Accessed December 2017. http://www.fieldoperations.net/project-details/project/philadelphia-navy-yards-central-green.html.
44. "Shoemaker Green." Shoemaker Green | SITES. Accessed February 18, 2017. http://sustainablesites.org/certified-sites/shoemaker.
45. "Friends Center." Greenroofs.com Projects - Friends Center. Accessed December 2017. http://www.greenroofs.com/projects/pview.php?id=617.
46. Marshall, Kimberly. "How Much Do Microfiltration and Ultrafiltration Membrane Systems Cost?" Samco Tech. December 06, 2017. Accessed December 2017. https://www.samcotech.com/how-much-do-microfiltration-and-ultrafiltration-membrane-systems-cost/.
47. Learn More. Accessed December 2017. http://www.ciragreen.com/learn-more.html.
48. "SCS Runoff Curve Number Method - Introduction." Professor Patel. Accessed December 23, 2017. http://www.professorpatel.com/curve-number-introduction.html.